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Validation of HVOF WC/Co Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Aircraft Landing Gear

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14. ABSTRACT

Hard chromium electroplating is extensively used by aircraft manufacturers and military maintenance depots to provide wear and/or corrosion resistance or to restore dimensional tolerance to components. However, chrome plating utilizes hexavalent chromium, which is a highly toxic carcinogen, and increasingly stringent environmental and worker-safety regulations are making chrome plating more expensive for the DoD. This document constitutes the final report on a project to qualify high-velocity oxygen-fuel (HVOF) thermal spray WC/Co coatings as a replacement for hard chrome plating on landing gear components. Extensive fatigue, wear, corrosion, impact, and hydrogen embrittlement test results comparing the WC/Co coatings against hard chrome are presented. The results of rig and flight-testing of HVOF WC/Co coatings on landing gear components are also presented. In general, the performance of the WC/Co coatings was superior to hard chrome. Producibility issues such as stripping, grinding, and non-destructive inspection of the coatings were addressed. Cost/benefit analyses indicate that military repair depots that overhaul landing gear can realize substantial savings by converting from hard chrome to HVOF. Specifications were developed for the WC/Co powder, the coatings deposition parameters, and the grinding of the WC/Co coatings.

15. SUBJECT TERMS

Thermal spray, HVOF thermal spray; WC/Co coatings; Hard chrome plating; Electrolytic hard chrome; Landing gear; Fatigue; Wear; Corrosion; Hydrogen embrittlement

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LIST OF ACRONYMS

AMS	Aerospace Materials Specification
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CAC	constant amplitude test
CBA	cost/benefit analysis
CCAD	Corpus Christi Army Depot
CFR	Code of Federal Regulations
C-HCAT	Canadian Hard Chrome Alternatives Team
DARPA	Defense Advanced Research Projects Agency
DI	de-ionized
DND	Department of National Defence
DOD	Department of Defense
DOE	design of experiments
ECAM	Environmental Cost Accounting Methodology
EHC	electrolytic hard chrome
EPA	U.S. Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FPI	fluorescent penetrant inspection
FTSH	fatigue test spectrum hours
GEAE	GE Aircraft Engines
gph	gallons per hour
GTE	gas turbine engine
HCAT	Hard Chrome Alternatives Team
HE	hydrogen embrittlement
HVOF	high-velocity oxygen-fuel
IARC	International Agency for Research on Cancer
IC	Industry Canada
IRR	internal rate-of-return
JG-PP	Joint Group on Pollution Prevention
JTP	joint test protocol
JTR	joint test report
ksi	thousands of pounds per square inch
LGJTP	Landing Gear Joint Test Protocol
MLG	main landing gear
MJTR	Materials Joint Test Report
MRO	maintenance, repair and overhaul
NADEP-CP	Naval Aviation Depot Cherry Point
NADEP-JAX	Naval Aviation Depot Jacksonville
NAVAIR	Naval Air Systems Command
NLG	nose landing gear
NPV	net present value
NRL	Naval Research Laboratory
NTS	notch tensile strength
OEM	original equipment manufacturer

OMB	U.S. Office of Management and Budget
OO-ALC	Ogden Air Logistics Center
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
PPE	personal protective equipment
psi	pounds per square inch
PVD	physical vapor deposition
rpm	rotations per minute
SAE	Society of Automotive and Aerospace Engineers
scfh	standard cubic feet per hour
SFH	simulated flight hours
TAT	turn-around time
TWA	time-weighted average

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1. Background

The replacement of hard chrome plating in aircraft manufacturing activities and maintenance depots is a high priority for the U.S. Department of Defense (DOD) and the Canadian Department of National Defence (DND). Hard chrome plating is a technique that has been in commercial production for over 50 years. It is a critical process that is used both for applying hard coatings to a variety of aircraft components in manufacturing operations and for general rebuild of worn or corroded components that have been removed from aircraft during overhaul. In particular, chrome plating is used extensively on landing gear components such as axles, hydraulic cylinders, pins and races. Chromium plating baths contain chromic acid, in which the chromium is in the hexavalent state, with hexavalent chromium (hex-Cr) being a known carcinogen having a level of toxicity greater than arsenic or cadmium. During operation, chrome plating tanks emit a hex-Cr mist into the air, which must be ducted away and removed by scrubbers. Wastes generated from plating operations must be disposed of as hazardous waste and plating operations must abide by U.S. Environmental Protection Agency (EPA) emissions standards and Occupational Safety and Health Administration (OSHA) permissible exposure limits (PEL).

A significant lowering of the hex-Cr PEL would most likely have the greatest cost impact on military and commercial repair facilities. Such a change has been expected for several years but has not yet been issued by OSHA. In anticipation of the change, in 1995 a Navy/Industry task group under the coordination of the Naval Sea Systems Command studied the technical and economic impact of a reduction in the hex-Cr PEL. At the time, a reduction in the 8-hour time-weighted average (TWA) from the existing 100 $\mu g/cm^3$ to between 0.5 and 5.0 $\mu g/cm^3$ was being considered. The Navy/Industry task group performed the following tasks:

- Identified the manufacturing and repair operations, materials and processes that are used in Navy ships, aircraft, other weapons systems and facilities where worker exposure to hex-Cr would be expected
- Developed data on current worker exposure levels to hex-Cr using OSHA Method 215
- Estimated the technical and economic impact of the anticipated reductions in hex-Cr exposure on Navy ships, aircraft, other weapons systems and facilities
- Identified future actions required to comply with the anticipated PEL reductions

The following operations were identified as having the potential for exposing workers to hex-Cr:

- Metal cleaning (including abrasive blasting and grinding) of chromate-coated materials
- Electroplating of chromium
- Painting and application of chromate paints and coatings
- Welding, thermal spraying and thermal cutting

The following conclusions were reached by the task group:

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- Regulated areas for hex-Cr would have to be created in much greater numbers than have been required for cadmium or lead exposure
- Local exhaust ventilation, which is the presently available engineering control, is not completely effective in reducing exposure to below 0.5 $\mu g/cm^3$ for many operations or even below 5 $\mu g/cm^3$ in some cases
- The inability of engineering controls to consistently reduce worker exposure below the anticipated PEL levels will significantly increase the use of respirators
- The costs of reducing the hex-Cr PEL will include costs for training, exposure monitoring, medical surveillance, engineering controls, personal protective equipment, regulated areas, hygiene facilities, housekeeping and maintenance of equipment. There will also be costs due to reduced efficiency of not only the operations involving hex-Cr but adjacent operations and personnel as well.
- The estimated costs for compliance with a PEL of 0.5 $\mu g/cm^3$ at Navy facilities include an initial, one-time cost of about $22,000,000 and annual costs of about $46,000,000 per year.
- The estimated costs for compliance with a PEL of 5.0 $\mu g/cm^3$ at Navy facilities include an initial, one-time cost of about $3,000,000 and annual costs of about $5,000,000 per year
- In addition to the greatly increased cost that would be associated with chrome plating, turnaround times for processing of components would be significantly increased as well, impacting mission readiness.

Although OSHA has delayed issuance of new hex-Cr permissible exposure limits, recent studies have clearly shown that there are a significant number of excess deaths at the current PEL of 0.1 mg/m^3 for hex-Cr emissions in plating facilities. For example, the August 2000 issue of the American Journal of Industrial Medicine contained a report on a study of 2,357 workers over a 30-year period which correlated the incidence of cancer with hex-Cr exposure. An analysis of the study was conducted by the Navy Environmental Health Center and it was their conclusion that the study appeared to support a lowering of the PEL to less than 0.001 mg/m^3. Although OSHA has not issued a schedule for issuance of a proposed new hex-Cr PEL, it appears clear that ultimately the PEL will have to be lowered.

Previous research and development efforts [1.1, 1.2] had established that high-velocity oxygen-fuel (HVOF) thermal spray coatings are the leading candidates for replacement of hard chrome. Using commercially available thermal spray systems HVOF thermal spraying can be used to deposit both metal alloy and ceramic/metal (e.g., WC-Co) coatings that are dense and highly adherent to the base material. They also can be applied in thicknesses in the same range as that currently being used for chrome plating. Although there are a wide number of applications for these coatings, their qualification as an acceptable replacement for hard chrome plating has not been adequately demonstrated, particularly for fatigue-sensitive aircraft components.

The Environmental Security Technology Certification Program (ESTCP) was established as a program of the U. S. Department of Defense (DOD) in December 1993. The ESTCP, which is managed by the Deputy Under Secretary of Defense for Installations and Environment, demonstrates and validates lab-proven technologies that target the most urgent DOD environmental needs. These technologies provide a return on

investment through reduced environmental, safety, and occupational health (ESOH) risks; cost savings; and improved efficiency. The new technologies typically have broad application both to the DOD sustainment community and industry.

In order to conduct the advanced development work required for qualification of the HVOF coatings, a project entitled, "Tri-Service Dem/Val of Chromium Electroplating Replacements," principally sponsored by ESTCP, was established in March 1996. A project team, designated the Hard Chrome Alternatives Team (HCAT) was established to execute the project. From 1996 to early 1998, the HCAT acquired and installed HVOF thermal spray systems at the Naval Aviation Depot in Cherry Point, North Carolina (NADEP-CP) and the Corpus Christi Army Depot (CCAD). It also performed some generic fatigue and corrosion testing on HVOF WC-17Co (83 wt% WC particles in a 17 wt% Co matrix) and Tribaloy 400 (60% Co, 28% Mo, 9% Cr, 3% Si) coatings compared to electrolytic hard chrome (EHC) coatings. Substrate materials included 4340 steel, 7075 aluminum alloy, and PH13-8 stainless steel. From a fatigue standpoint the HVOF coatings generally performed better than the EHC coatings (i.e., there was a reduced fatigue debit with respect to the non-coated material for the HVOF coatings compared to the EHC coatings). In B117 salt fog corrosion studies, the performance of the WC/Co was comparable to the EHC, with the Tribaloy 400 slightly worse. In atmospheric corrosion studies, the WC/Co performed substantially better than the EHC, with the Tribaloy 400 comparable to the EHC.

While these studies were valuable, it was realized in early 1998 that because hard chrome plating was being used on such a wide variety of aircraft components, it would be impossible to develop one test plan or conduct one series of tests that would address all materials and component qualification requirements. It was therefore decided to develop separate projects related to categories of aircraft components onto which hard chrome was being used. At the same time, the DOD Joint Group on Pollution Prevention (JG-PP) decided to partner with the HCAT on development and execution of the various projects. JG-PP is chartered by the Joint Logistics Commanders (JLC) to coordinate joint service pollution prevention activities during the acquisition and sustainment of weapons systems. It was jointly determined by the HCAT and JG-PP that the first projects to be executed would be on landing gear and propeller hubs, with projects on hydraulic actuators and helicopter dynamic components to come later. (Note that there is a fifth project being executed between the HCAT and DOD Propulsion Environmental Working Group on hard chrome replacement on gas turbine engine components.)

Since the technology to be demonstrated and validated as a hard chrome replacement had already been selected (namely HVOF thermal spray), then the first activity for the landing gear project was the development of the Joint Test Protocol (JTP) which would delineate all of the materials and component testing requirements necessary to qualify the HVOF coatings on landing gear components for all types of DoD aircraft. Table 1-1 and Table 1-2 summarize the target hazardous material, current process, application, current specifications, and affected defense systems programs (delineated according to the U.S. DOD aviation depot at which the overhaul of the landing gear from that aircraft takes place).

A stakeholder meeting was held at the Naval Research Laboratory in July 1998 to discuss the types of materials testing that would be required and also explore what avenues were

available for component testing. It was subsequently decided that the JTP would be developed and issued in two parts, with Part I for materials (i.e., coupon-type) testing and Part II for component testing.

Table 1-1. Landing Gear Aircraft Applications

Target HazMat	Current Process	Application	Current Specifications	Candidate Parts/ Substrates
Hexavalent Chromium	Hard Chromium Electro-plating	Rebuilding Worn Components Wear-resistant Coating Corrosion-resistant Coating	DOD-STD-2182 MIL-C-14538C MIL-C-20218F MIL-H-83282 MIL-STD-1501C QQ-C-320B	Landing Gear

Table 1-2. Defense System Programs Potentially Affected

CCAD	NADEP Cherry Point	NADEP JAX:	Ogden ALC	
SH-60 (Navy)	AV-8B	E-6	A-7	F-16
UH-60	C-130	EA-6B	A-10	F-22
	E-2/C-2	F-14	B-1B	F-104
	H-1	F-18	B-2	F-106
	H-46	P-3	B-52	F-111
	H-53	S-3	C-5	H-3
	H-60	T-45	C-17	H-53 (USAF/Navy)
	P-3		C-130	KC-135
			C-141	T-37
			F-5	T-38
			F-15	

The Canadian Government, through the Department of National Defence (DND) and Industry Canada (IC), facing environmental restrictions on chrome plating similar to the U.S., also became interested in qualifying HVOF thermal spray coatings on aircraft landing gear both for manufacturing and maintenance operations. The Canadian Government formed their own project team, designated the Canadian Hard Chrome Alternatives Team (C-HCAT), and a partnership was formed between both projects. A formal Project Arrangement, conducted under the auspices of the U.S.-Canadian Research and Technology Projects Memorandum of Understanding (MOU), was

negotiated and executed in March 1999. In order to achieve maximum impact, the joint project concentrated on landing gear systems common to both U.S. and Canadian aircraft and on landing gear components that are supplied by Canadian companies for use in U.S. aircraft.

In terms of qualifying specific types of HVOF coatings by the two teams, it was decided that the U.S. HCAT would evaluate WC/Co (83%/17%) HVOF coatings whereas the C-HCAT would evaluate WC/CoCr (86%/10%4%) HVOF coatings. It was further decided that all materials testing would be incorporated into one document constituting Part I of the JTP, but that there would be a clear delineation between the testing being conducted by the U.S. HCAT and that conducted by the C-HCAT.

The following organizations were involved with the development of the U.S. portion of the Landing Gear JTP:

- Naval Research Laboratory (NRL)
- Air Force Materiel Command
- Naval Air Systems Command
- Air Force Landing Gear Single Item Manager OO-ALC/LIL
- Naval Aviation Depot- Jacksonville (NADEP-JAX)
- Naval Aviation Depot- Cherry Point (NADEP-CP)
- Ogden Air Logistics Center (OO-ALC)
- Naval Air Warfare Center, Aircraft Division, Patuxent River
- Air Force Research Laboratory
- Rowan Technology Group
- GE Aircraft Engines (GEAE)
- National Technical Systems (NTS)
- Boeing Defense (St. Louis)

The following are the principal organizations that constitute the C-HCAT and which participated in the development of the Canadian portion of the Landing Gear JTP:

- Department of National Defence
- Industry Canada
- Technology Partnerships Canada
- Messier-Dowty
- Goodrich
- Heroux, Inc.
- Orenda Aerospace Corporation
- National Research Council of Canada

Part I of the Landing Gear JTP [1.3] was organized in sections, with each section devoted

to the type of test being conducted. Most sections were divided into two subsections, the first for the U.S. portion of the testing and the second for the Canadian portion of the testing. The testing by the two teams on the two different HVOF coatings was meant to be very similar, but there were some differences. The following were the different sections in the Materials JTP:

1. Introduction
2. Fatigue
3. Corrosion
4. Wear
5. Impact Testing
6. Hydrogen Embrittlement

Section 3 of this report, essentially reproducing the Materials Joint Test Report (MJTR) (without appendices), provides the results of all of the testing conducted in accordance with Part I of the JTP. It only includes the U.S. portion of the testing and thus in general only includes results for WC-Co (83%/17%) coatings compared to EHC coatings. A separate C-HCAT MJTR has been issued by the Canadian Department of National Defence on the WC/CoCr coatings. Section 4 of this report describes the results of extended testing carried out to address the issue of coating integrity that was found during the JTP fatigue measurements.

Although there was no formal Component Joint Test Protocol, there were a number of component rig and flight tests conducted on landing gear components and these are described in Section 5 of this report.

In addition to materials and component testing, in order to transition HVOF thermal spray technology to military repair facilities, it was necessary to address several producibility issues including stripping and grinding of the WC/Co coatings, determining their compatibility with different fluids used for cleaning and other operations, and performing non-destructive inspection of the WC/Co coatings. The results of investigations in these areas are described in Section 1.

Another issue related to successful transitioning of the HVOF technology was relative costs compared to hard chrome plating and determining the return-on-investment by implementing the WC/Co coatings. The results of a detailed cost/benefit analysis are presented in Section 1.

To ensure uniformity of coating characteristics and performance between military facilities using HVOF thermal spray of WC/Co, standards and specifications were developed for the WC/Co and WC/CoCr powder and for the deposition conditions. These are presented in Section 8.

Finally, a review of issues associated with implementation of HVOF WC/Co coatings in repair facilities is presented in Section 9.

In this report, there are a number of references to specific standards related to materials processing, coating deposition, and testing. These are summarized in Table 1-3.

Table 1-3. Applicable Materials Processing, Coating Deposition and Test Standards

ASTM Standards:
ASTM E466: Standard Practice for Fatigue testing
ASTM B117: Standard Practice for Salt Spray (fog) Apparatus, Operating
ASTM G85: Standard Practice for Modified Salt Spray (FOG)
ASTM B537: Standard Practice for Ranking Electroplated Panels Subject to Atmospheric Exposure
ASTM D3170: Standard Practice for Coatings, Chipping Resistance
ASTM F519: Mechanical Hydrogen Embrittlement Testing of Plating Processes and Aircraft Maintenance Chemicals, Method for

Boeing Aircraft Corporation (BAC) Standards:
P.S. 15169: Heat treatment specifications for Aermet 100 steel
P.S. 11501: Application of polystyrene resin impregnation sealer on EHC coatings
BAC 5851: Deposition of HVOF thermal spray coatings
BAC 5855: Low-stress grinding of coatings

Military Specifications:
DOD-STD-2182: Engineering Chromium Plating (Electrodeposit for Repair of Shafting)
MIL-C-14538: Chromium Plating, Black (Electrodeposited)
MIL-C-20218: Chromium Plating, Electrodeposited, Porous
MIL-H-83282: Hydraulic Fluid, Fire Resistant, Synthetic Hydrocarbon Base
MIL-STD-1501: Chromium Plating Low Embrittlement, Electrodeposition
MIL-STD-866: Grinding of Chrome Plated Steel and Steel Parts Heat Treated to 180,000 psi or over
MIL-STD-867: Temper Etch Inspection
MIL-STD-1504: Abrasive Blasting
QQ-C-320: Chromium Plating (Electrodeposited)
QQ-N-290: Nickel Plating (Electrodeposited)
MIL-A-8625: Anodic Coatings for Aluminum and Aluminum Alloys

SAE Standards:
AMS-81934: Bearings, Sleeves, Plain and Flanged, Self-lubricating, General Spec for
AMS-4640: Aluminum Bronze, Bars, Rods, Shapes, Tubes, and Forgings 81.5Cu-10.0 Al-4.8 Ni-3.0 Fe, Drawn and Stress Relieve (HR50) or Temper Anneals
AMS-2432: Shot Peening, Computer Controlled
AMS-6875: Heat treating of high strength Steels
SAE J400: Gravelometer Testing

Other specifications:
GM9540P/B: GM corrosion test

One final item to note in this section is that the commercial aircraft industry has independently moved toward qualifying HVOF thermal spray coatings (especially WC/Co and WC/CoCr) on landing gear components. For OEM applications, Boeing has specified WC/CoCr on the landing gear for the 767-400, and the current design for the new Airbus A380 has established WC/CoCr as the preferred coating on its landing gear. For commercial maintenance and repair operations (MRO) at airlines, Boeing has approved HVOF WC/Co and WC/CoCr coatings up to 0.010" thick subject to the coating facility obtaining a Boeing qualification certification. Delta Airlines is one of several U.S. airlines that have aggressively moved toward inserting HVOF into its production MRO operations. Table 1-4 is a summary of the various applications of HVOF coatings in the commercial aircraft industry.

Table 1-4. Commercial Programs Affected and Potentially Affected by HVOF Chrome Replacement

Approved	Potentially affected
Boeing - Steering collars, flap and slat tracks, pins, sleeves, fittings (>100 items)	Bombardier Dash 8 (OEM and MRO)
Boeing 676-400 landing gear (HVOF WC-CoCr)	Airbus 380
Commercial airliner landing gear MRO – HVOF approved by Boeing up to 0.010" thick.	
HVOF WC-CoCr approved by Delta for MRO on landing gear	
Bombardier Q400 Global Express flap tracks	

1.1. References

1.1 "High Velocity Oxy Fuel Final Results Report," Final Report issued by Science Applications International Corporation under Government Contract F09603-90-D2215, Oklahoma City Air Logistics Center, Tinker Air Force Base, May 25, 1994

1.2 "Hard Chrome Coatings: Advanced Technology for Waste Elimination," Final Report issued by Northwestern University, Evanston, IL, under DARPA Contract MDA972-93-1-0006, 1996

1.3 "Joint Test Protocol, Validation of WC/Co and WC/CoCr HVOF Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Aircraft Landing Gear, Part I: Materials Testing." Prepared by Hard Chrome Alternatives Team for Environmental Security Technology Certification Program, Revision A, September 1999

2. Technology Description

2.1. Technology Development and Application

Technology background and theory of operation: HVOF is a standard commercial thermal spray process in which a powder of the material to be sprayed is injected into a supersonic flame of a fuel (usually hydrogen, propylene or kerosene) as shown in Figure 2-1. The powder particles are accelerated to high speed and soften in the flame, forming a dense, well-adhered coating on the substrate. The coating material is usually a metal or alloy (such as Tribaloy or stainless steel), or a cermet (such as cobalt-cemented tungsten carbide, WC/Co). The technology is used to deposit coatings about 0.003" thick on original equipment manufacturer (OEM) parts, and to rebuild worn components by depositing layers up to 0.015" thick.

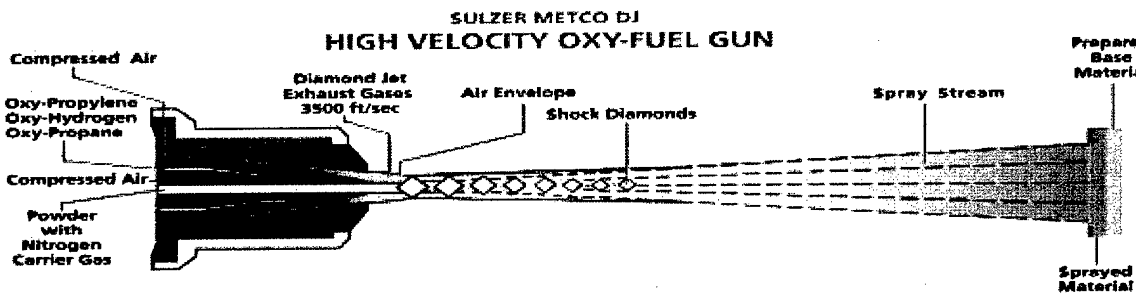


Figure 2-1. Schematic of HVOF Gun and Process (Sulzer Metco DiamondJet)

Applicability: HVOF was originally developed primarily for gas turbine engine (GTE) applications. The primary thermal spray processes are Flame Spray, Plasma Spray, Arc Spray, HVOF and the recently-developed cold spray. The original high velocity spray technology was the pulsed deposition detonation gun (D-gun) developed by Union Carbide (later Praxair). The quality of the wear and erosion resistant spray coatings produced by this method was much better than the lower speed methods, and continuous flame HVOF was developed as a competitive response.

The original applications for HVOF were wear components in GTEs, such as shafts and bearing journals. As the availability and use of the technology grew, it began to be applied to a wide range of other types of coatings and applications, including a variety of aircraft components such as flap and slat tracks, landing gear and hydraulics for commercial aircraft. It is now being used in many applications outside the aircraft industry, such as industrial rolls and vehicle hydraulics. The original aircraft wear applications, primarily used by Boeing, were for otherwise-intractable spot problems that neither the original alloy nor chrome plate could solve.

The technology can be used to spray a wide variety of alloys and cermets. It is limited for high temperature materials such as oxides, most of which cannot be melted in the flame. The areas to be coated must be accessible to the gun – i.e., they must be line-of-sight.

Material to be replaced: HVOF coatings are used to replace hard chrome plate (especially using carbide cermets and high temperature oxidation-resistant Tribaloys).

The combination of HVOF NiAl with an overlayer carbide is also used to replace the combination sulfamate Ni/hard chrome. HVOF coatings can also be used to replace some hard Ni and electroless Ni coatings on such components as flap tracks and propeller hubs. In the HCAT program, the primary application is hard chrome replacement.

2.2. Process Description

Installation and operation: The HVOF gun can be hand-held and used in an open-fronted booth. However, the supersonic gas stream is extremely loud and requires that the operator use very good ear protection. For this reason the unit is usually installed on a six-axis robot arm in a sound-proof booth, programmed and operated remotely. Most depots already use this type of booth for their existing plasma spray operations. Since the method is frequently used for cylindrical items, the most common arrangement is to rotate the component on a horizontal rotating table and move the gun up and down the axis.

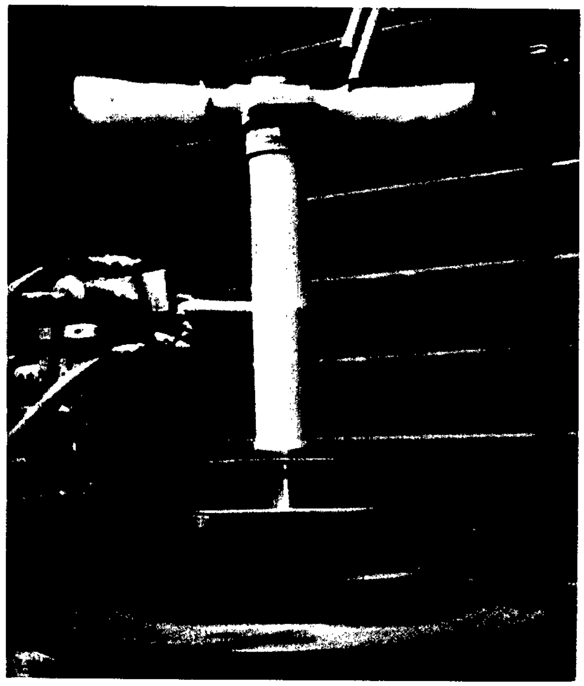


Figure 2-2. HVOF Spray of Landing Gear Inner Cylinder

Facility design: The installation requires:

- A soundproof booth. Booths are typically 15 feet square, with a separate operator control room, an observation window, and a high volume air handling system drawing air and dust out of the booth through a louvered opening (shown in Figure 2-2).
- Gun and control panel. The gun burns the fuel and oxygen inside its combustion chamber and injects the powder axially into the flame. The gas exits the gun at supersonic speed, while the particles are accelerated to high velocity but usually remain subsonic. The control panel controls the gas flows, cooling water, etc.
- Powder feeder. Powder is typically about 60μm in diameter and is held in a powder feeder, which meters the powder to the gun at a steady rate, carried on a gas stream. Two powder feeders are commonly used to permit changeover from one coating to another without interrupting the spraying.
- 6-axis industrial robot and controller. Most installations use an industrial robot to manipulate the gun and ensure even spraying. The robot is often suspended from above to leave the maximum possible floor space for large items.
- Supply of oxygen. This is frequently a bulk storage container outside the building. Alternatively bottled gas can be used, but because of the high usage rate of up to 2,000 scfh (see Table 2-1), even a standard 12-bottle setup lasts only a

few hours in production.

- Supply of fuel gas or kerosene (bottled or bulk). Hydrogen is the most common fuel, supplied in bulk or in bottles. Praxair TAFA guns use kerosene, which is significantly cheaper and less dangerous.
- Dust extractor and bag-house filter system. The air extracted from the booth is laden with overspray – particles that have failed to stick to the surface (often 20-50% of the total sprayed). The air is blown into a standard bag house, often located outside the building, where the dust is removed.
- Dry, oil-free compressed air for cooling the component and gun. Air cooling prevents the components being overheated (temperatures must be kept below about 400°F for most high strength steels).
- Water cooling for gun. Not all guns are water cooled, but most are.

The facility must be capable of supplying the material pressures and flows of Table 2-1. Standard commercial equipment currently in service already meets these requirements. Equipment vendors are able to supply turnkey systems.

Table 2-1. Optimized Deposition Conditions for WC/17Co (DJ 2600 and JP 5000 HVOF guns)

Equipment	**Gun**	Model 2600 hybrid gun	Model 5220 gun with 8" nozzle
	Console	Model DJC	Model 5120
	Powder feeder	Model DJP powder feeder	Model 5500 powder feeder
Powder feed	**Powder**	Diamalloy 2005	Stark Amperit 526.062
	Powder Feed Rate:	8.5 lb/hr	80 gm/min (325 rpm, 6 pitch feeder screw)
	Powder Carrier Gas	Nitrogen	Argon
	Carrier gas pressure	148 psi	50 psi
	Flow rate	28 scfh	15 scfh
Combustion Gases	**Fuel**	Hydrogen	Kerosene, Type 1-K
	Console supply pressure		162-168 psi
	Gun supply pressure	135 psi	121-123 psi
	Flow rate	1229 scfh	5.0 gph
	Oxidizer	Oxygen	Oxygen
	Pressure	148 psi	138-140 psi
	Mass flow	412 scfh	2000 scfh
Gun Compressed Air	**Pressure**	105 psi	
	Mass flow	920 scfh	
Gun Cooling Water Flow	**Flow rate**	5.3-5.7 gph (factory set)	8.3-8.7 gph
	Water Temperature to Gun:	65-80°F typical (ground water, temp varies)	64-72°F
Specimen Rotation		2,336 rpm for round bars (0.25 inch dia.) – 1835 in/min surface speed	600 rpm for round bars (0.25 inch diam.); 144 rpm for rectangular bars (at 6.63 inch diam.)
Gun Traverse Speed		400 linear in/min for round bars	70 in/min for round bars
Spray Distance		11.5 inches	18 inches
Cooling Air	**Pressure**	90-110 psi	90-110 psi
	Location	2 stationary nozzle tips at 6 inches pointed at coating area	2 gun-mounted air jets at 14 inches; 1 stationary air jet at 4-6 inches pointed at coating area

Performance: From Table 2-1, HVOF guns deliver about 8-10 pounds per hour (4-5 kg per hour) of powder, of which 65% typically enters the coating, for a coating rate of

about 6 pounds per hour (3 kg per hour). For a common 0.010" WC/Co rebuild coating (which will be sprayed to a thickness of 0.013-0.015"), an HVOF gun can deposit about 900 square inches per hour. This permits coating the 23" long, 4" diameter bearing surface of an F-18 nose landing gear (NLG) in about 30 minutes, compared with about 15 hours for chrome plating.

Specifications: The following specifications and standards apply to HVOF coatings:

- Prior to the HCAT program, the only aerospace specifications were those issued by prime contractors such as Boeing, whose BAC 5851 thermal spray specification, supported by BMS 10-67G powder specification, is still one of the most quoted standards
- AMS 2447 was developed with the assistance of the HCAT team and issued by SAE in 1998. It is now a widely used standard in the aerospace industry.
- In order to provide specifications for spraying high strength aircraft steels at depots and vendors, HCAT has worked through SAE to promulgate several standards:
    - Aerospace Materials Specification (AMS) 2448, issued in 2003, is a specification for HVOF spraying of high strength steel.
    - AMS 7881 and AMS 7882 are powder specifications that support AMS 2448.
    - An AMS standard for grinding of HVOF coatings will be issued in a few months.

Training: Just as plating shops typically have several personnel who handle masking, racking, demasking, etc., it is common for HVOF shops to have 3 or 4 technicians dedicated to masking and spraying. HVOF training is essential and is usually provided by equipment vendors such as Praxair and Sulzer Metco. Training is also available through the Thermal Spray Society. Depot personnel taking part in the HCAT program have been trained by Jerry Schell, thermal spray coatings expert at GE Aircraft Engines. Since thermal spray is a more complex technology than electroplating, plating line personnel cannot be transferred successfully to an HVOF shop without extensive retraining.

Health and safety: The process does not produce air emissions or toxic wastes. Co powder is an International Agency for Research on Cancer (IARC) Group 2B material, which means that "The agent (mixture) is possibly carcinogenic to humans", whereas Cr^{6+} is an IARC Group 1 material, "Known to be carcinogenic to humans". However, the OSHA PEL for Co (8hr TWA) of 0.1 mg(Co)/m^3, is lower than the 1 mg(Cr)/m^3 for metallic chrome, and is the same as the 0.1 mg(Cr)/m^3 for Cr^{6+}. Unlike chrome plating, the Co is not emitted into the air. Excess Co-containing powder is drawn from the spray booth and captured in the bag house. Nevertheless personnel should wear a dust respirator when handling the powder, working in the booth, or grinding the coating. While the powders are usually about 60μm in diameter, they can break apart on impact, producing 10μm or smaller particles. The American Welding Society recommends the use of a respirator complying with American National Standards Institute (ANSI) Z88.2

Ease of operation: Since in commercial systems the entire system is programmable, including the gun control and robot, it is generally easy to operate. The operator must create masking (usually shim stock shadow masks) and must develop the correct spray parameters and gun motions. While vendors supply standard operating conditions for different materials, these may have to be optimized experimentally for new materials and powders, and must be adjusted for different components to ensure proper coating speed and gun traverse rate. Small diameter components, for example, must be rotated faster than large ones to maintain the same deposition rate and coating structure. In this respect operating an HVOF system is considerably more complex than electroplating.

2.3. Previous Testing of the Technology

Prior to the HCAT program, HVOF technology had been successfully used by Boeing for a number of years for their commercial aircraft and by GEAE for GTEs. In the period 1993-1996 Keith Legg, Bruce Sartwell, GEAE, Cummins Diesel and Corpus Christi Army Depot carried out an evaluation of chrome alternatives [2.1], funded by the Defense Advanced Research Projects Agency (DARPA). The program evaluated HVOF, physical vapor deposition (PVD) and laser cladding, and concluded that HVOF was the best overall alternative for use in depots and most OEM aircraft applications. At the beginning of the HCAT program, Lufthansa successfully completed flight tests of HVOF coatings on commercial landing gear and Delta began to carry out similar flight tests.

2.4. Advantages and Limitations of the Technology

Replacing hard chrome plating is a great deal more complex than simply putting down a hard coating. The alternative must not only work technically, but it must fit with the entire life cycle of use and maintenance, and it must be a reasonable, mature technology for depot use. The advantages and limitations of HVOF are summarized in Table 2-2.

2.5. References

2.1 "Hard Chrome Coatings: Advanced Technology for Waste Elimination," Final Report issued by Northwestern University, Evanston, IL, under DARPA Contract MDA972-93-1-0006, 1996

Table 2-2. Advantages and Limitations of HVOF as a Chrome Replacement

Advantages/strengths	Disadvantages/limitations
Technical:	
Higher hardness, better wear resistance, longer overhaul cycle, less frequent replacement	Brittle, low strain-to-failure – can spall at high load. Issue primarily for carrier-based aircraft
Better fatigue, corrosion, embrittlement	Line-of-sight. Cannot coat IDs
Material can be adjusted to match service requirements	More complex than electroplating. Requires careful QC
Depot and OEM fit:	
Most depots already have thermal spray expertise and equipment	WC-Co requires diamond grinding wheel. Only HVOF alloys can be plunge ground
Can coat large areas quickly	
Can be chemically stripped	
Many commercial vendors	
Environmental:	
No air emissions, no high volume rinse water	Co toxicity

3. Materials Testing

3.1. Summary of Tests Conducted

As indicated in Section 1, this section reproduces the Materials Joint Test Report, but without the appendices. The entire report [3.1] is available from the HCAT web site at www.hcat.org. Table 3-1 summarizes the tests conducted under the JTP for the three coatings tested on the three substrates of major interest for landing gear. 4340 and

Table 3-1. Summary of Tests Conducted in JTP

	Substrates/coatings						
	4340			300M		A100	
Tests	WC-Co	WC-CoCr	T400	WC-Co	WC-CoCr	WC-Co	WC-CoCr
Deposition	**X**	**X**	**O**	**X**	**X**	**X**	**X**
Fatigue	**X**	**X**	**O**	**X**	**X**	**X**	**X**
Corrosion	**X**	**X**	**O**	**X**	**X**	**X**	**X**
Wear	**X**	**X**	**O**				
Impact	**X**	**X**					
Embrittlement	**X**	**X**					

X LG JTP

O Generic

4340M are primarily used on older landing gear and hydraulic actuators, 300M is commonly used on most modern landing gear, while Aermet 100 is used on some modern Navy gear.

3.2. Coating optimization and characterization

The optimized deposition conditions for the hydrogen-fueled Sulzer Metco Diamond Jet DJ 2600 HVOF gun used at most of the depots and the Praxair kerosene-fueled JP 5000 gun used at Ogden ALC are shown in Table 3-2. These guns were optimized for WC-17Co by design of experiment methods as described below.

Table 3-2. Optimized Deposition Conditions for WC-17Co - DJ 2600 and JP 5000 HVOF guns

Equipment	**Gun**	Model 2600 hybrid gun	Model 5220 gun with 8" nozzle
	Console	Model DJC	Model 5120
	Powder feeder	Model DJP powder feeder	Model 5500 powder feeder
	Injector	#8	
	Shell	#8	
	Insert	#8	
	Siphon plug	#8	
	Aircap	DJ2603	
Powder feed	**Powder**	Diamalloy 2005	Stark Amperit 526.062
	Powder Feed Rate:	8.5 lb/hr	80 gm/min (325 rpm, 6 pitch feeder screw)
	Vibrator setting		30
	Tube	DJP 116	
	Pick-up shaft	"E"	
	Air Vibrator setting	20 psi	
	Powder Carrier Gas	Nitrogen	Argon
	Carrier gas pressure	148 psi	50 psi
	FMR	55	
	Flow rate	28 scfh	15 scfh
Combustion Gases	**Fuel**	Hydrogen	Kerosene, Type 1-K
	Console supply pressure		162-168 psi
	Gun supply pressure	135 psi	121-123 psi
	Combustion Chamber Pressure		100-102 psi
	FMR	53.4	
	Flow rate	1229 scfh	5.0 gph
	Oxidizer	Oxygen	Oxygen
	Pressure	148 psi	190-235 psi console supply reading 138-140 psi gun supply pressure
	FMR	28.7	
	Mass flow	412 scfh	2000 scfh (corrected flow at 210 psi: 1940 to 2075 actual flow tube reading, depending on console supply pressure reading)
Gun Compressed Air	**Pressure**	105 psi	
	FMR	FMR – 50.5	
	Mass flow	920 scfh	
Gun Cooling Water Flow	**Flow rate**	5.3-5.7 gph (factory set)	8.3-8.7 gph
	Water Temperature to Gun:		
	In	65-80°F typical (ground water, temp varies)	64-72°F
	Out	77-100 °F typical	117-125 °F
	Delta	12-20 °F (~ 14 °F typical)	51-54 °F
Specimen Rotation		2,336 rpm for round bars (0.25 inch dia.) – 1835 in/min surface speed	600 rpm for round bars (0.25 inch diam.); 144 rpm for rectangular bars (at 6.63 inch fixture diam.)
Gun Traverse Speed		400 linear in/min for round bars	70 in/min for round bars; 17 in/min for rectangular bars
Spray Distance		11.5 inches	18 inches
Cooling Air	**Pressure**	90-110 psi	90-110 psi
	Location	2 stationary nozzle tips at 6 inches pointed at coating area	2 gun-mounted air jets at 14 inches; 1 stationary air jet at 4-6 inches pointed at coating area

3.2.1. Rationale/Background

3.2.1.1. HVOF Application

As in all coating methods, the properties and performance of the coating depends on both the coating material and the deposition conditions. Optimal coating properties can therefore only be obtained when the critical deposition parameters are in the proper range. In chrome plating the coating properties are primarily governed by solution chemistry, temperature, and current density. HVOF spraying is more complex to optimize since there are many more variables in the deposition process. For this reason, HVOF coatings were optimized in the HCAT program by a Design of Experiment (DOE) approach, which permits optimum conditions to be identified from a limited set of test runs, obviating the need for a full test matrix that would entail many hundreds of deposition tests.

3.2.1.2. HCAT Coating Optimization and Deposition Philosophy – Fatigue

In order to optimize a coating, it is important to decide at the outset what property, or set of properties, is to be optimized. This is especially true for thermal spray coatings, where it has been found, for example, that a coating optimized for minimum wear can behave poorly in fatigue. Within the HCAT, the fatigue critical nature of applications such as landing gear, actuators, propeller hub components and gas turbine engine parts was quickly identified as the major life limiting characteristic. This does not eliminate the need to evaluate other characteristics such as corrosion, wear, hydrogen embrittlement, etc. but coating optimization initially concentrated on fatigue performance, with modifications for other properties as necessary. This approach was adopted as the philosophy of the HCAT from the onset of the program, as evidenced by the heavy concentration on fatigue in the test protocols.

Coating deposition for the various team members was optimized by Jerry Schell of GE Aircraft Engines, an expert in thermal spray optimization. The coating optimization process began with the initial "Northwestern or generic" protocol in 1996 and has been evolving to the present time. A design of experiment (DOE) test methodology (which will be discussed in a later section) was chosen as the mechanism to provide an optimized coating deposit. The variables in the process were identified and experiments conducted to determine the best parameter set for optimum results. Work was required for the varied commercial systems to demonstrate capability across the available equipment sets. Thus, data summarized in this section covers both the JP-5000 (Praxair TAFA) and the DJ 2600 (Sulzer Metco) systems, and represents work conducted at varied locations (Hill AFB, CCAD, Cherry Point, and Hitemco) in the 1996-1999 time frame. This resulted in the final coating parameters for the majority of the Landing Gear Joint Test Protocol (LG JTP).

Optimization of the process is carried out for three important reasons:

1. To define a thermal spray process that will achieve the desired performance and property goals.

2. To establish manufacturing robustness and the process window for a reliable process.
3. To understand the process and trends that give an indication of (and can later be used as) a trouble shooting guide. When parameters are identified as significant, these variables will be the first areas of investigation in problem solving.

In optimizing the HVOF process, it is important to understand the difference between the general output of the process and the characteristics/properties of the final coating deposit. As stated earlier, the final goal of the coating optimization was maximized fatigue performance with close emphasis on other properties such as corrosion, wear, etc. However, when the coating is initially sprayed, only a set of simple measurements can be used for quality control of the process, as follows:

- ❑ Microstructure (primarily measurement of porosity, unmelted particles, and oxides)
- ❑ Hardness (both macro and micro)
- ❑ Almen Strip (residual stress)
- ❑ Substrate Temperature (during coating)
- ❑ Deposition Rate

Between them, these measurements have proved to be adequate to define the coating for the purpose of quality control. It makes technical sense that characteristics such as microstructure and hardness will ultimately determine coating performance in areas such as wear or corrosion resistance, while residual stress and substrate temperature are known to strongly influence fatigue. Thus, even though the ultimate goal is enhanced fatigue performance, that performance can be ensured indirectly by measuring other coating properties for quality control.

Since the deposition process is known to be uniform and stable, these measurements can be made on test samples set up to see the same deposition conditions as the components to be coated. These test samples may be fabricated prior to deposition (for daily spray booth qualification), or sprayed during coating deposition on components (for quality control).

3.2.1.3. Fatigue Cycle Life vs. Fatigue Coating Integrity

As with any optimization procedure, there is a learning phase to the process and issues are sometimes identified that are unexpected from previous experience and planning. This was the situation in developing precise testing documentation for measurement of the Almen Strip and Temperature during spraying (procedures detailed later in this section).

Another major property issue identified during optimization was differentiation between fatigue coating integrity and fatigue cycle life (further detailed in the fatigue section). The initial Northwestern-generic protocol addressed fatigue performance with primary emphasis on fatigue cycle life, the typical S-N curves which are generated to illustrate load vs. cycle performance. This followed the initial work performed by Boeing where 3-4 coating suppliers were qualified based upon the Q.C. tests listed earlier and

satisfactory fatigue life cycle life performance. Both sets of data were focused upon a non-aggressive R ratio of .1 and stress levels to maximum of 180 ksi.

The LG JTP also addressed fatigue performance with emphasis on cycle life. However, the R ratio was increased to a more aggressive level of –1, while cyclic stress was increased, in some cases to the yield point. This resulted in concerns with coating spalling or delamination and a category or classification for fatigue coating integrity. It must be emphasized that the LG JTP coatings were optimized for fatigue cycle life, NOT fatigue coating integrity. Details of the optimization process and some subsequent plans to address the fatigue coating integrity issue will be discussed and summarized in this section.

3.2.2. Test methodology

3.2.2.1. DOE Methodology

For this optimization study, the design of experiment (DOE) methodology was chosen as the vehicle to deliver the best spray parameter set. This method is used in many manufacturing environments when numerous variables exist and there is insufficient time and financial resources to analyze each individual process input (i.e. to carry out a full matrix test). Pre-DOE experiments are usually run on a iterative basis to determine the limits of the various parameters and which have the most significant effect on the output of the process. A DOE matrix is then designed using standard experimental design protocols in which the variables selected are usually assigned high and low values for the numerous DOE test runs. Statistical analysis is applied and each variable assigned a rank as to the effect on the final process output. In subsequent experimentation, insignificant variables are eliminated from the analysis and the final outcome is a full parameter set for the process in question. For the HCAT program the experimental design was done using commercial software made by Minitab, Inc.

3.2.2.2. HVOF Optimization

3.2.2.2.1. General

The DOE method revolves around process inputs and outputs as illustrated below with a limited list for the HVOF spray technology:

Table 3-3. Inputs and Outputs for Design of Experiment HVOF Optimization

Input	Output
Powder size	Hardness
Gas flow	Microstructure
Gas ratio-fuel to oxygen	Almen strip
Spray distance	Tensile
Carrier gas flow	Coating deposition rate
Air flow	
Traverse speed	

As stated earlier, even with the DOE methodology, there must be a general starting or reference point. This was provided by the earlier HVOF work conducted by Boeing and some general experience from Jerry Schell of GEAE. With this knowledge and the ultimate goal of fatigue performance, three QC outputs were identified as the major drivers to achieve the end goal:

Hardness – tends to be a general gage of wear resistance, but more importantly an indicator of carbide solutioning and phase change

Almen Strip – indication of coating residual stress

Substrate Temperature – should be below 350°F to avoid degrading substrate fatigue in high strength steels

This information shaped the methodology involved for this optimization, which included:

Pre-DOE – A series of general experimental runs to achieve a common-sense understanding of the process. For example, it would not make sense to pick a parameter range for the HVOF system setting that would not allow the gun to spray in an efficient manner or provides no Almen Strip response. This initial set identifies some reasonable responses for the actual DOE experimentation.

Actual DOE – When a reasonable set of process inputs and ranges have been identified, a number of runs/experiments are conducted according to a test matrix defined by the DOE software. Outputs are analyzed and trends determined. Dependent upon time and funding, further more refined studies can be run or the process fine-tuned at this point.

Validation Runs – Using the optimum determined from the DOE, a small set of runs is made to verify the parameter set, and repeat spray cycles are conducted to establish consistency.

3.2.2.3. General Example: CCAD Analysis

A typical example of this process is represented by the work conducted at CCAD in the initial optimization of the DJ 2600 system.

Table 3-4 Optimization Parameters for the CCAD DJ 2600 Analysis

FACTORS:		Levels -1	Levels +1	Levels CPt
A	Traverse speeds	20 ipm	40 ipm	30 ipm
B	Spray distance	8 inch	12 inch	10 inch
C	Stoic Ratio	0.38	0.6	0.44
D	Combustion Gas	1550 scfh	2000 scfh	1775 scfh
E	Air flow	735 scfh	965 scfh	850 scfh
F	Carrier gas flow	42.6 scfh	71 scfh	56.8 scfh
G	Turntable RPM	90 RPM	250 RPM	170 scfh
H	Powder Feed Rate**	5.4 lbs/hr	10.7 lbs/hr	15.8 lbs/hr
I	Powder size	Amp526.0(Lot 10362	2005NS Lot 53792	2005NS Lot 53558
J	Part diameter	2 inch	6.63 inch	4.31 inch
K	Spray pattern length	11 inch	19 inch	15 inch

*Grit blast | 24 grit, 35 psi

** Actual PFR needs TBD in light of TWIN 10 uncertainities;
(theorhetical values are given above)

FIXED:

Metco VF grit blast surface prep procedure*

Substrate is 4340 steel, 260-280 ksi

Powder type is WC-17Co, agglomerated and sintered

Spray angle is 90 degrees

100 psi air, 5 AJs @6 inch spaced over 8-12 inch coupon area

Carrier gas equiv N_2 mass flow for N_2 or Argon

N2 x 1.42 = Ar

RESPONSES:	RELATED CTG FUNCTION:
1) Part temperature	Fatigue
2) Almen strip	Fatigue, ctg residual stress
3) Hardness, HV_{300}	Wear
4) Coating dep/pass	Cost
5) Porosity	Ctg quality, corrosion
6) Oxides	Ctg quality
7) Carbides	Ctg quality, wear
8) Tensile bond	Adhesion/cohesion

Table 3-4 represents the variables that were analyzed in the CCAD study. As illustrated by the data, a high/low range was selected for parameters such as gas flow, powder feed rate, part stand-off distance (distance from end of gun to part), etc. The inputs are then placed into a matrix as typified in Table 3-5 and the runs made in the random order specified to eliminate any bias which might exist.

Trends and relationships are determined by statistical analysis as will be summarized in the subsequent test results section.

3.2.3. Test Results

3.2.3.1. General Sequence

The evolving optimization process for LG coatings involved the systems, locations, and time frames as listed in Table 3-6. In discussing each location, the general matrix design and effect on the three major outputs of Almen, Temperature and Microhardness will be presented. No pre DOE or final optimization fine tuning will be summarized but the final spray parameter set is listed.

Table 3-5 Actual Runs for CCAD Experimentation

			C	D	E	F	A	G	J	B	K	H	I
Actual			3	4	5	6	1	7	10	2	11	8	9
Run Order	Std Order	Random	STOIC	COMB G	Air scfh	CG scfh	TrvSp ipm	TT Sp rpm	Part diam	SD inches	SpPattL,in	PFR lb/hr	Pwdr size
1	16	1	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
2	14	2	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
3	12	11	0.38	1550	735	30	20	90	2.00	8	11	5.5	Diam 53792
4	8	13	0.60	2000	965	30	20	250	6.63	8	11	15.8	Diam 53792
5	10	5	0.38	1550	965	50	40	250	6.63	8	19	5.5	Stark 10362
6	7	10	0.60	2000	735	50	20	250	2.00	12	11	5.5	Stark 10362
7	6	15	0.60	1550	965	50	40	90	2.00	12	11	15.8	Diam 53792
8	15	12	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
9	13	14	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
10	1	6	0.60	1550	735	50	40	250	2.00	8	19	15.8	Stark 10362
11	9	16	0.38	2000	965	50	20	90	2.00	8	19	15.8	Stark 10362
12	2	3	0.38	2000	785	30	40	90	6.63	12	11	15.8	Stark 10362
13	3	8	0.60	1550	965	30	20	90	6.63	12	19	5.5	Stark 10362
14	11	9	0.38	1550	735	50	20	250	6.63	12	19	15.8	Diam 53792
15	4	7	0.60	2000	735	50	40	90	6.63	8	19	5.5	Diam 53792
16	5	4	0.38	2000	965	30	40	250	2.00	12	19	5.5	Diam 53792
17	17	17	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
18	18	18	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
19	10 repeat		0.38	1550	965	50	40	250	6.63	8	19	5.5	Stark 10362

Table 3-6 DOE Sites and Locations

Location	System	Time Frame
Hill AFB	JP 5000	1996
CCAD	DJ 2600	1997-8
Hitemco	DJ 2600	1998-9
NADEP-CP	DJ 2600	1998-9

Jerry Schell, an HCAT team member from GEAE, was selected to manage the optimization procedure based upon his previous experience with HVOF and his extensive knowledge of the DOE methodology with special emphasis on thermal spray processes

3.2.3.2. Northwestern/Generic Protocol at Hill AFB JP 5000

3.2.3.2.1. General Test Results

The initial Northwestern Protocol was run to optimize fatigue for HVOF process optimization and not for any specific aircraft application. The R ratio of 0.1 was therefore selected as the test condition. This work was conducted at Hill AFB in the 1996 time frame.

Table 3-7 to Table 3-9 summarize the DOE for the Hill work.

Table 3-7. DOE Matrix for Hill AFB Work in 1996

Design 1: Use L8 design 8 runs total

FACTORS:		Levels -1	Levels +1
A	Fuel (gph)	4	5.5
B	PFR (gm/min)	5	8
C	Nozzle (inches)	4	8
D	Oxygen (scfh)	1900	2100
E	Overlap (RPM)	90	144
F	Spray Distance (inches)	15	18
G	Powder Size (µm)	31	39

FIXED:
54 grit alumina grit blast at 40 psi, 6 inches
Substrate is 4340 steel, 260-280 ksi

Spray angle is 90 degrees
100 psi cooling air, 4 AJs @ 6 inch spaced over coupon area

Spray pattern length	Approximately 13 inch
Fixture diameter	6 inch

RESPONSES:	RELATED CTG FUNCTION:
1) Part temperature	Fatigue
2) Almen strip	Fatigue, ctg residual stress
3) Hardness, HV_{300}	Wear
4) Coating dep/pass	Cost
5) Porosity	Ctg quality, corrosion
6) Oxides	Ctg quality
7) Carbides	Ctg quality, wear
8) Tensile bond	Adhesion/cohesion

Table 3-8. Summary of Results for the Hill JP 5000 DOE

Hill AFB JP 5000

	Parameters	Thk/ Pass (% RESPONSES)	CY6 Temp (% RESPONSES)	Almen (% RESPONSES)	HV300 (% RESPONSES)	AVG	Rank
A	Fuel	6.8	43.4	25.5	42.8	29.6	
B	PFR	47.8	2.5	9.4	12.8	18.1	
C	Nozzle	13.4	27.0	22.7	0.2	15.8	
D	Oxygen	4.5	0.9	6.1	20.6	8.0	5th
E	Overlap	22.8	0.3	1.8	1.9	6.7	5th
F	Spary Distance	2.1	23.2	27.6	14.0	16.7	
G	Powder Size	2.6	2.7	7.0	7.7	5.0	6th

Effects Range	Thk/ Pass	CY6 Temp	Almen	HV300
Average	0.644	409	12.6	1054
Lower	0.357	301	6.5	855
Upper	0.917	530	18	1220
Mean +/- X %	42.4	29.6	42.9	15.7

Table 3-8 summarizes the data form the Hill DOE. Table 3-9 Listing of the random run order for the varied parameter sets. Table 3-10 lists the final coating parameters for the JP 5000 system.

Table 3-9. Run Order for Hill AFB Work

		FACTOR						
		Fuel	PFR	Nozle	Oxygen	Overlap	Sp Dist	Powder Size
Run No.	Std Order	gph	gm/min	inches	scfh	RPM	inches	µm
1	3	4	5	4	1900	90	15	31
2	5	4	5	4	2100	144	18	39
3	8	4	8	8	1900	90	18	39
4	2	4	8	8	2100	144	15	31
5	7	5.5	5	8	1900	144	15	39
6	1	5.5	5	8	2100	90	18	31
7	4	5.5	8	4	1900	144	18	31
8	6	5.5	8	4	2100	90	15	39

3.2.3.2.2. General Discussion

As expected, combustion gas and stand-off distance are the major factors in the spray process. The data for microhardness, almen strip values, and substrate temperature identifies these variables as the critical parameters for control and the obvious areas to investigate in future problem troubleshooting. There is also a degree of process robustness with the analysis indicating that a fairly wide range of values can be used to achieve a consistent end result.

Three other areas should also be noted:

- Deposition rate of the coating is obviously controlled not only by powder feed rate but traverse speed of the part being sprayed. This traverse rate dependency is evident in data from all systems and guns. This will have a substantial effect on almen and substrate temperature because of the heat being transferred to the part as the gun sweeps across it. It is therefore critical to keep deposition rate constant in spraying test bars, almen strips, or parts to best approximate a consistent and repeatable process
- For the JP 5000 analysis, the nozzle length was a significant factor for all three critical outputs. Only the 4 and 8 inch lengths were tested, with the 8 inch dimension providing the optimum coating deposit.

- Stoichiometry (i.e. hydrogen/oxygen ratio in the flame) was also identified as a major factor in microhardness results. This affects the melting of the cobalt binder and dissolution of the carbides. Non-optimal ratios can drive the carbides into solution, resulting in poor hardness or toughness.

Table 3-10. Final Parameters for Hill AFB JP 5000

JP5000 Process Parameters for WC-17%Co Fatigue Specimens	
Equipment	Model 5220 gun with 8" nozzle Model 5120 Model 5500 powder feeder
Powder feed	Stark Amperit 526.062 80 gm/min (325 rpm, 6 pitch feeder screw) 30 Argon 50 psi 15 scfh
Combustion Gases	Kerosene, Type 1-K 162-168 psi 121-123 psi 100-102 psi 5.0 gph Oxygen 190-235 psi console supply reading 138-140 psi gun supply pressure 2000 scfh (corrected flow at 210 psi: 1940 to 2075 actual flow tube reading, depending on console supply pressure reading)
Gun Compressed Air	
Gun Cooling Water Flow	8.3-8.7 gph 64-72°F 117-125°F 51-54°F
Specimen Rotation	600 rpm for round bars (0.25 inch diam.); 144 rpm for rectangular bars (at 6.63 inch fixture diam.)
Gun Traverse Speed	70 in/min for round bars; 17 in/min for rectangular bars
Spray Distance	18 inches
Cooling Air	90-110 psi 2 gun-mounted air jets at 14 inches; 1 stationary air jet at 4-6 inches pointed at coating area

3.2.3.3.CCAD DOE 1998

3.2.3.3.1. General Test Results

In preparation for the LG JTP and to assist in assimilating HVOF technology into the depots, an interim optimization was run at the CCAD facility to optimize spray parameters on the DJ 2600 system. Although the JP 5000 and DJ2600 are both HVOF

systems, there is enough difference in the design to require optimization of both systems. Table 3-11 summarizes the DOE matrix for the CCAD work.

Table 3-11. DOE Matrix for CCAD 1998

FACTORS:		Levels -1	Levels +1	Levels C Pt
A	Traverse speeds	20 ipm	40 ipm	30 ipm
B	Spray distance	8 inch	12 inch	10 inch
C	Stoic Ratio	0.38	0.6	0.44
D	Combustion Gas	1550 scfh	2000 scfh	1775 scfh
E	Air flow	735 scfh	965 scfh	850 scfh
F	Carrier gas flow	42.6 scfh	71 scfh	56.8 scfh
G	Turntable RPM	90 RPM	250 RPM	170 scfh
H	Powder Feed Rate**	5.4 lbs/hr	10.7 lbs/hr	15.8 lbs/hr
I	Powder size	Amp526.0(Lot 10362	2005NS Lot 53792	2005NS Lot 53558
J	Part diameter	2 inch	6.63 inch	4.31 inch
K	Spray pattern length	11 inch	19 inch	15 inch

*Grit blast | 24 grit, 35 psi

** Actual PFR needs TBD in light of TWIN 10 uncertainities; (theorhetical values are given above)

FIXED:

Metco VF grit blast surface prep procedure*

Substrate is 4340 steel, 260-280 ksi

Powder type is WC-17Co, agglomerated and sintered

Spray angle is 90 degrees

100 psi air, 5 AJs @ 6 inch spaced over 8-12 inch coupon area

Carrier gas equiv N_2 mass flow for N_2 or Argon

N2 x 1.42 = Ar

RESPONSES:	RELATED CTG FUNCTION:
1) Part temperature	Fatigue
2) Almen strip	Fatigue, ctg residual stress
3) Hardness, HV_{300}	Wear
4) Coating dep/pass	Cost
5) Porosity	Ctg quality, corrosion
6) Oxides	Ctg quality
7) Carbides	Ctg quality, wear
8) Tensile bond	Adhesion/cohesion

Table 3-12 summarizes random run order for the DOE matrix of the CCAD work.

Table 3-12. Random Run Listing for CCAD DOE

			C	D	E	F	A	G	J	B	K	H	I
Actual			3	4	5	6	1	7	10	2	11	8	9
Run Order	Std Order	Random	STOIC	COMB G	Air scfh	CG scfh	TrvSp ipm	TT Sp rpm	Part diam	SD inches	SpPattL.in	PFR lb/hr	Pwdr size
1	16	1	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
2	14	2	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
3	12	11	0.38	1550	735	30	20	90	2.00	8	11	5.5	Diam 53792
4	8	13	0.60	2000	965	30	20	250	6.63	8	11	15.8	Diam 53792
5	10	5	0.38	1550	965	50	40	250	6.63	8	19	5.5	Stark 10362
6	7	10	0.60	2000	735	50	20	250	2.00	12	11	5.5	Stark 10362
7	6	15	0.60	1550	965	50	40	90	2.00	12	11	15.8	Diam 53792
8	15	12	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
9	13	14	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
10	1	6	0.60	1550	735	50	40	250	2.00	8	19	15.8	Stark 10362
11	9	16	0.38	2000	965	50	20	90	2.00	8	19	15.8	Stark 10362
12	2	3	0.38	2000	785	30	40	90	6.63	12	11	15.8	Stark 10362
13	3	8	0.60	1550	965	30	20	90	6.63	12	19	5.5	Stark 10362
14	11	9	0.38	1550	735	50	20	250	6.63	12	19	15.8	Diam 53792
15	4	7	0.60	2000	735	50	40	90	6.63	8	19	5.5	Diam 53792
16	5	4	0.38	2000	965	30	40	250	2.00	12	19	5.5	Diam 53792
17	17	17	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
18	18	18	0.49	1775	850	40	30	170	4.31	10	15	10.7	Diam 53558
19	10 repeat		0.38	1550	965	50	40	250	6.63	8	19	5.5	Stark 10362

The responses for the DOE are summarized in Figure 3-1., Figure 3-2., and Figure 3-3..

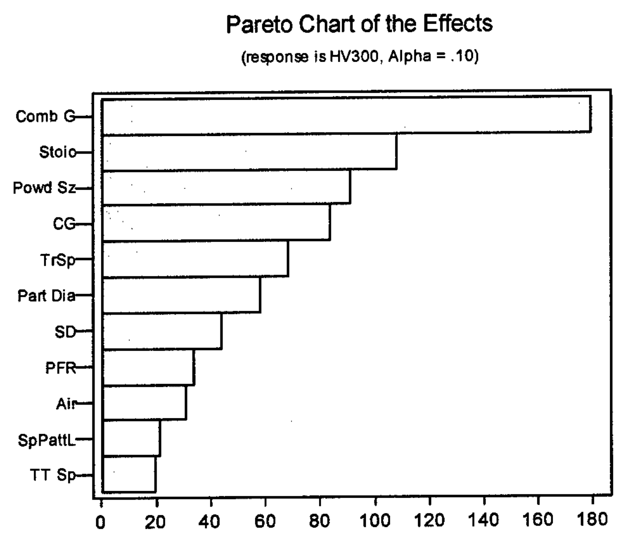


Figure 3-1. Microhardness Response for CCAD DOE

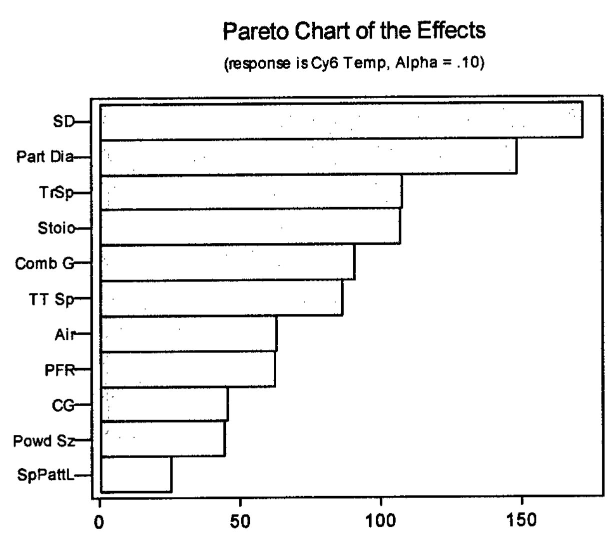


Figure 3-2. Substrate Temperature Response for CCAD DOE

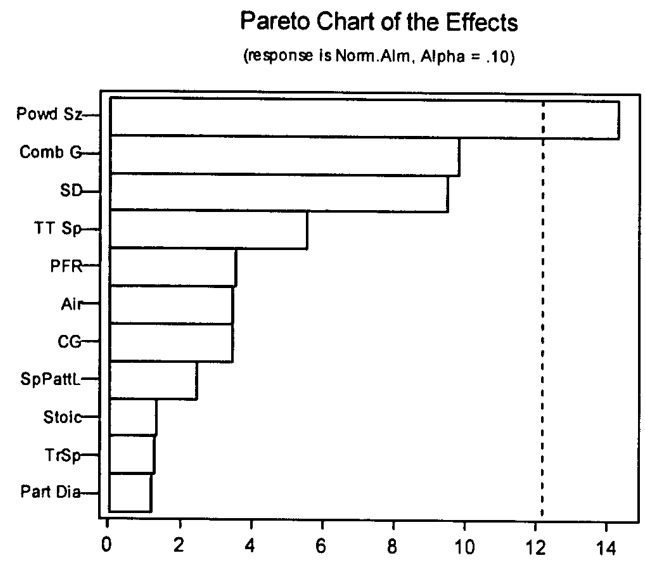


Figure 3-3. Almen Strip Response for CCAD DOE

3.2.3.3.2. General Discussion

As expected, combustion gas and stand-off distance are the major factors in the spray process. The data for microhardness, almen strip values, and substrate temperature identifies these variables as the critical parameters for control and the obvious areas to investigate in future problem troubleshooting. The analysis shows a robust process with that a fairly wide range of values that can be used to achieve a consistent end result.

Three other areas should also be noted:

- Deposition rate of the coating is obviously controlled not only by powder feed rate but traverse speed of the part being sprayed. This traverse rate/deposition rate dependency is evident in data from all systems and guns. This will have a substantial effect on Almen and Substrate Temperature because of the heat being transferred to part. It is therefore critical to keep deposition rate constant in spraying test bars, Almen strips, or parts to best approximate a consistent and repeatable process .
- For the CCAD analysis, the powder size/distribution was a significant factor for the Almen strip output indicating a variation in the residual stress state of the coating. This variable can be controlled by use of material form one powder manufacturer which is common in the thermal spray industry. However, this indicates that a change to another manufacturer will require some process revalidation and is also an indicator that this parameter should also be added to the problem trouble shooting guide.
- Stoichiometry was also identified as a major factor in microhardness results. Stoichiometry is the ratio of fuel gas to oxygen in the gun, and because it controls

flame temperature, it affects melting of the matrix Co and dissolution of the carbides. High flame temperatures tend to solution the carbides, resulting in hardness changes and alloying of the binder, both of which affect mechanical properties of the coating. Stoichiometry must therefore be included in the process control.

Table 3-13. Final Summary of Factors in CCAD DOE

		% RESPONSES					
Parameters		Thk/ Pass	CY6 Temp	Almen	HV300	AVG	Rank
A	TrvSp ipm	9.3	11.3	2.3	9.3	8.0	4th
B	SD inches	6.4			5.9	11.9	3rd
C	STOIC	3.7	11.2	2.3		8.0	4th
D	COMB G	5.3	9.5			14.2	
E	Air scfh	6.0	6.6	6.2	4.2	5.8	5th
F	CG scfh	10.3	4.7	6.2	11.4	8.2	4th
G	TT Sp rpm	7.4	9.1	9.9	2.6	7.2	4th
H	PFR lb/ hr		6.5	6.4	4.6	8.0	4th
J	Pwdr size	11.3	4.6		12.4	13.5	
K	Part diam			2.2	7.9	11.2	3rd
L	SpPattL,in	6.8	2.6	4.4	2.8	4.2	5th
		100.0	100.0	100.0	100.0	100.0	
Effects Range		Thk/ Pass	CY6 Temp	Almen	HV300		
Lower		0.168	325	7.2	1024		
Upper		0.746	496	21.5	1203		
Mean +/- X %		63.2	20.8	49.8	8.0		

A summary of the CCAD work is presented in Table 3-13, and more details can be found in the Appendix 1 of the Joint Test Report [3.1].

3.2.3.4. LG DOE at Hitemco: 1998-1999 DJ 2600 System

The DOE work at Hitemco was the final coating analysis prior to coating of the fatigue, corrosion and wear specimens. The investigation was performed to verify the outcome of the DOE at CCAD and to finalize the process prior to test bar coating deposition. Table 3-14 presents the DOE matrix.

Table 3-14. DOE Matrix for Hitemco Analysis

Design 1: Use L8 design plus Center Points 11 runs total

FACTORS:		-1	+1	C Pt
			Levels	
A	Surf Speed,Feed Rate	1335, 5.1	1835, 3.5	1585 ipm, 4.3
B	Combustion Gas	1525 scfh	1825 scfh	1675 scfh
C	Stoic Ratio	0.405	0.485	0.445
D	Spray Distance	10 inch	13 inch	11.5 inch

A Factor:	Turntable RPM	Robot Spd ipm	mm/sec	Robot % @ 750 mm/sec	Spots/Rev
(-1)	212	25	10.6	1.41%	5.1
C Pt	252	35	14.8	1.98%	4.3
(+1)	292	50	21.2	2.82%	3.5

B,C) Factor Combinations:

Comb Gas	Stoic Ratio	Hyd SCFH	Oxy SCFH	Air SCFH	Point (CG,SR)
1675	0.445	1159	332	920	(0, 0)
1525	0.405	1085	258	920	(-1,-1)
1525	0.485	1027	314	920	(-1,+1)
1825	0.405	1299	342	920	(+1,-1)
1825	0.485	1229	412	920	(+1,+1)

FIXED:

54 grit alumina grit blast at 40 psi, 6 inches
Substrate is 4340 steel, 260-280 ksi
Powder size/type is WC-17Co, Diamalloy 2005, Lot 54480
Powder Feed Rate** 8.5 lbs/hr
Spray angle is 90 degrees
100 psi cooling air, 4 AJs @ 6 inch spaced over coupon area
Carrier gas N_2 at 148 psi, 55 flow, air vib @ 20 psi
Spray pattern length Approximately 13 inch
Fixture diameter 2 inch

RESPONSES:	RELATED CTG FUNCTION:
1) Part temperature	Fatigue
2) Almen strip	Fatigue, ctg residual stress
3) Hardness, HV_{300}	Wear
4) Coating dep/pass	Cost
5) Porosity	Ctg quality, corrosion
6) Oxides	Ctg quality
7) Carbides	Ctg quality, wear
8) Tensile bond	Adhesion/cohesion

Table 3-15 represents the random run sequence for the Hiemco DOE.

Table 3-15. Random Runs for Hitemco DOE

		A factor		(B,C) Combined Factors			D factor
Run No.	Std.Ord	Turn Table RPM	Robot Trav Sp mm/s	Hydrogen psi/FMR	Oxygen psi/FMR	Air psi, FMR	Sp Dist inches
1	9	252	14.8	135 psi, 50.4	148 psi, 23.1	105 psi, 50.5	11.5
2	1	212	10.6	135 psi, 47.2	148 psi, 17.8	105 psi, 50.5	10
3	2	292	21.2	135 psi, 47.2	148 psi, 17.8	105 psi, 50.5	13
4	3	212	10.6	135 psi, 56.5	148 psi, 23.8	105 psi, 50.5	13
5	4	292	21.2	135 psi, 56.5	148 psi, 23.8	105 psi, 50.5	10
6	10	252	14.8	135 psi, 50.4	148 psi, 23.1	105 psi, 50.5	11.5
7	5	212	10.6	135 psi, 44.6	148 psi, 21.8	105 psi, 50.5	13
8	6	292	21.2	135 psi, 44.6	148 psi, 21.8	105 psi, 50.5	10
9	7	212	10.6	135 psi, 53.4	148 psi, 28.7	105 psi, 50.5	10
10	8	292	21.2	135 psi, 53.4	148 psi, 28.7	105 psi, 50.5	13
11	11	252	14.8	135 psi, 50.4	148 psi, 23.1	105 psi, 50.5	11.5

Figure 3-4., Figure 3-5. and Figure 3-6. show the general trends for substrate temperature, almen strip and microhardness responses.

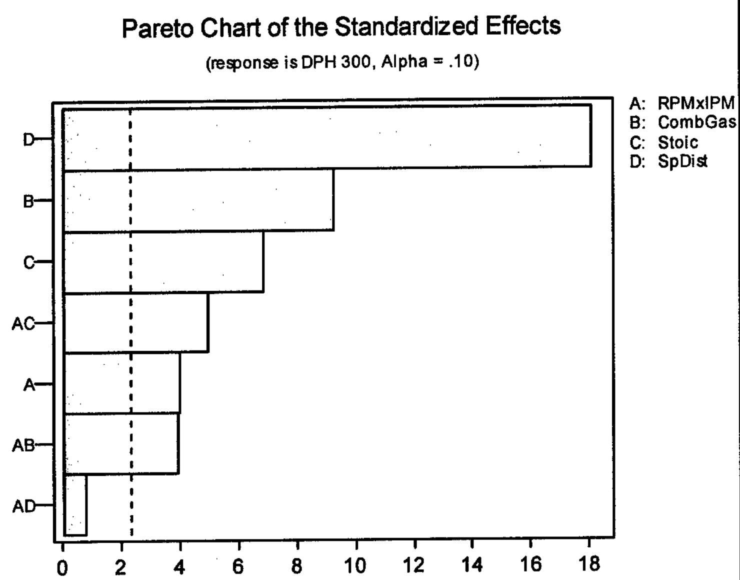


Figure 3-4. Microhardness Response for Hitemco DOE

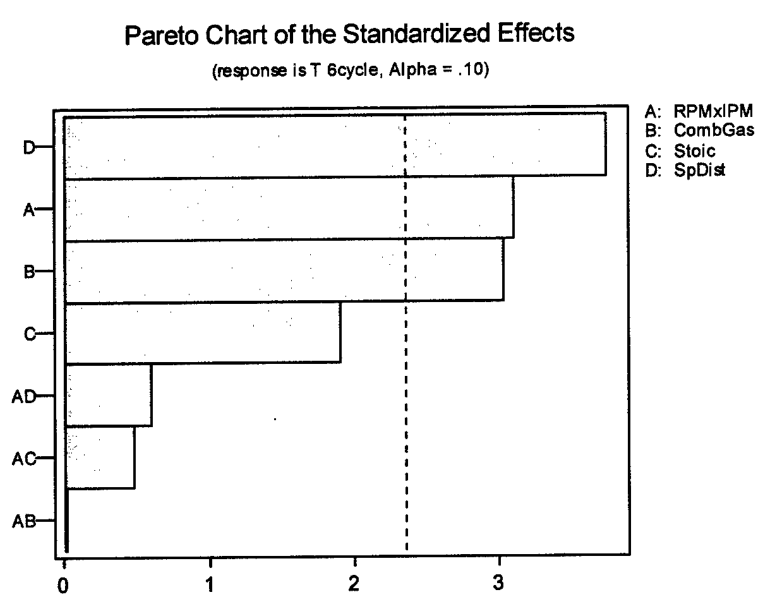


Figure 3-5. Substrate Temperature Response for Hitemco DOE

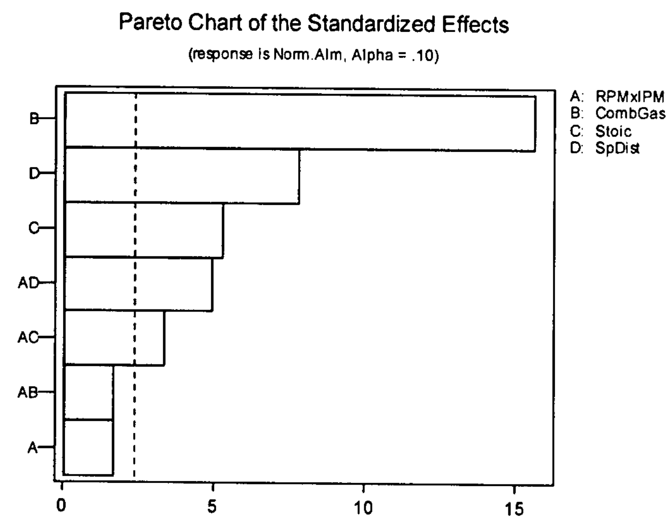


Figure 3-6. Almen Strip Response for Hitemco DOE

Table 3-16 is the final spray parameter set for the test bar spraying for the LG JTP.

Table 3-16. Final Deposition Parameters Hitemco LG JTP

Equipment	**Gun**	Model 2600 hybrid gun
	Console	Model DJC
	Powder feeder	Model DJP powder feeder
	Injector	#8
	Shell	#8
	Insert	#8
	Siphon plug	#8
	Aircap	DJ2603
Powder feed	**Powder**	Diamalloy 2005
	Powder Feed Rate:	8.5 lb/hr
	Tube	DJP 116
	Pick-up shaft	"E"
	Air Vibrator setting	20 psi
	Powder Carrier Gas	Nitrogen
	Carrier gas pressure	148 psi
	FMR	55
	Flow rate	28 scfh
Combustion Gases	**Fuel**	Hydrogen
	Gun supply pressure	135 psi
	FMR	53.4
	Flow rate	1229 scfh
	Oxidizer	Oxygen
	Pressure	148 psi
	FMR	28.7
	Mass flow	412 scfh
Gun Compressed Air	**Pressure**	105 psi
	FMR	FMR – 50.5
	Mass flow	920 scfh
Gun Cooling Water Flow	**Flow rate**	5.3-5.7 gph (factory set)
	Water Temperature to Gun:	
	In	65-80°F typical (ground water, temp varies)
	Out	77-100 °F typical
	Delta	12-20 °F (~ 14 °F typical)
Specimen Rotation		2,336 rpm for round bars (0.25 inch dia.) – 1835 in/min surface speed
Gun Traverse Speed		400 linear in/min for round bars
Spray Distance		11.5 inches
Cooling Air	**Pressure**	90-110 psi
	Location	2 stationary nozzle tips at 6 inches pointed at coating area

3.2.3.4.1. General Discussion

As expected, combustion gas and stand-off distance are the major factors in the spray process. The data for microhardness, Almen strip values, and substrate temperature identifies these variables as the critical parameters for control and the obvious areas to investigate in future problem troubleshooting. There is also a degree of process

robustness with the analysis indicating that a fairly wide range of values can be used to achieve a consistent end result.

Two other areas should also be noted:

- The deposition rate of the coating is obviously controlled not only by powder feed rate but traverse speed of the part being sprayed. This traverse rate/deposition rate dependency is evident in data from all systems and guns. This will have a substantial effect on Almen and substrate temperature because of the heat being transferred to the part. It is therefore critical to keep the deposition rate constant in spraying test bars, Almen strips, or parts to best approximate a consistent and repeatable process
- Stoichiometry was also identified as a major factor in microhardness results.

A summary of the Hitemco work can be found in Appendix 1 of the JTR [3.1].

3.2.3.5. Almen Strip and Temperature Measurement Procedures

Almen strip and substrate temperature control are two of the more critical areas for process control. In the initial HVOF trials, it was assumed that these measurements were well defined and would not create any inconsistencies. Subsequent experience has shown that this is not the case.

Almen strip results were found to be strongly influenced by preparation and spraying methods, leading to large systematic differences between spray sites. Factors to consider are:

- ❑ *Grit blasting of one side vs. both sides of the strip* This can result in a 3-4 mil difference in Almen results when spraying.
- ❑ *Orientation of the strip (i.e. torch traverse along or across the strip* This can result in a 0.001"-0.002" difference in Almen results when spraying.
- ❑ *Cleaning of Almen block* If not performed properly and frequently, coating will build up on the block, preventing proper thermal contact and leading to improper readings
- ❑ *Reduction in Almen Response with Increasing Thickness* As thickness increases, the Almen response appears to level off. Another almen strip type may be required for more substantial deflections
- ❑ *Normalized Almen Values* Based upon the issue of thickness, many initial values have been reported for the .003-.005" thickness range due to interest in those areas. However, values for Almen response can vary even over a .002" range. HCAT has therefore defined Almen stress as the value measured on a 0.005" thick coating.

It is common practice in many spray shops to measure substrate temperature with a contact probe at the end of the spray run. This approach provides no information on the true temperature excursions that occur during spraying. The HCAT team therefore adopted the approach of continuous infrared temperature measurement during spraying. For substrate temperature measurement, the following issues have been identified:

- *Use of Real time measurement vs. Touch Probe* Temperatures can be as much as 100° F hotter with instantaneous measurement (IR pyrometer) vs. touch probe after all spraying is complete.
- *Spot size of IR System* When spraying small test bars (as was required for this project), the spot size is normally bigger than the specimen diameter. This requires a compensation factor when spraying test bars. If the actual reading is used, it will give a false indication which is lower than the actual bar value and substrate overheating may result.
- *Co-ordination of Touch Probes and IR System Via Emissivity Corrections* As stated earlier, temperatures can be as much as 100° F hotter with instantaneous measurement (IR pyrometer) vs. touch probe after all spraying is complete. The IR unit must therefore be calibrated to define an emissivity setting that can be used as a default value. Although the IR system may not be an exact value, it can be used as a conservative guideline to control the process.

A complete guideline for Almen Strip/Substrate Temperature measurement can be found in Appendix 1 of the JTR [3.1].

3.2.4. Interpretation and Discussion

The optimization process for both the JP 500 and DJ 2600 produced the trends found in Table 3-17. The primary results are not unexpected for the substrate temperature and Almen as the amount of combustion gas will drive the achievable flame temperature, while spray distance (end of nozzle to part) will have a substantial effect on how much of that heat input is transferred to the part. It is very important to note that these trends were observed for both types of gun at three different locations.

Table 3-17. Primary and Secondary Determinants of Coating Properties

Property	Primary	Secondary
Almen	Combustion Gas Spray Distance	Nozzle Powder size
Microhardness	Combustion Gas Spray Distance	Powder size
Substrate temperature	Combustion Gas Spray Distance	Nozzle

The secondary effects of nozzle and powder size will be controlled by a standard choice for each of these parameters. When selected, these variables will be fixed but powder size must still be a part of the troubleshooting guide if size/particle distribution issues are identified at the powder vendor.

Fatigue was used as the most important factor in coating optimization. Initial focus was on fatigue cycle life which was achieved during the LG JTP evaluation. Additional work performed as part of HCAT by the Air Force Research Lab (AFRL) in the same time fame provided an example of problems that can be experienced during spraying. When

coating parameters were chosen that were optimized for wear performance rather than fatigue, HVOF cyclic fatigue lives were lower than chrome. Temperature control was also suspect. Respraying of bars at the same location with HCAT-optimized parameters and better temperature control resulted in satisfactory fatigue performance. This highlights not only the importance of process optimization, but also the importance of optimizing for the most critical performance parameters.

However, the question that still remains is coating integrity (which will be further discussed in the fatigue section of this report, and will be the subject of a subsequent report), and the need for process optimization for optimal integrity. Current industrial research indicates that areas such as phase content in the as-sprayed coating and the actual residual stress values in the test bar or part will be critical to coating integrity or cracking/delamination/spalling tendencies. These characteristics will be important in conjunction with particle velocity/temperature measurements that can be obtained with systems like the DPV 2000. It will be critical to investigate and understand these issues to produce an optimized coating which meets coating integrity criteria. This work, in conjunction with the present information, will provide a defined and robust set of parameters that can consistently produce reliable coatings on military hardware at the depot.

3.2.5. Significance

For implementation at military depots on flight critical hardware, a manufacturing process must be well defined and process variables highlighted for control. The coating optimization procedure has identified parameters that are critical and evaluated those variables with relation to manufacturing robustness and the future need for process troubleshooting. Further process understanding is in progress and will be required to fully comprehend and optimize the spray technology for fatigue coating integrity performance.

3.2.6. Conclusions

The HVOF process for WC-Co has been successfully optimized for both the JP 5000 and DJ 2600 systems with regard to many of the properties such as fatigue cycle life to achieve a repeatable process at varied locations.

More work is required concerning the issue of coating integrity (spalling and delamination) and process understanding concerning such variables as phase content, actual residual stressing the coating deposit, and velocity/temperature relationships (as measured by instruments such as the DPV 2000).

3.3. Fatigue data

3.3.1. Data Summary

Table 3-18. Quick Reference to Primary Data (Click blue links to jump to data)

Item	Item Number
Materials evaluated for fatigue testing	Table 3-20
Specimen types for fatigue testing	Figure 3-7, Figure 3-8,
Fatigue test matrix	Table 3-23
Representative data – 4340 steel	Figure 3-13. to Figure 3-17.
Representative data – Aermet 100 steel	Figure 3-18. to Figure 3-21.
Representative data – 300M steel	Figure 3-22. to Figure 3-25.
Summary of coating integrity analysis	Table 3-24

3.3.2. Test Rationale

Fatigue is a very critical property in the aerospace industry, because of the repeated cyclic loading for landing gear, actuators, airframe parts, and gas turbine engine components. Since fatigue performance is driven by material strength and is especially related to near-surface effects, fatigue-critical applications require careful definition and control of the thermal spray process to

1. minimize surface heating so as to prevent loss of mechanical properties due to overheating, and
2. deposit thermal spray coatings with compressive stress to minimize or eliminate any fatigue debit.

Although plasma spray processes have been widespread in the aerospace industry for many years, they have tended to be limited to non-fatigue critical applications, largely due to the heat input of the process and tensile coating stresses. The commercial development of the HVOF process, which relies more on kinetic than thermal energy for final coating properties and permits compressive coating stress, has started to move the design community towards thermal spray in fatigue-driven components. As a result HVOF coatings are now specified in numerous commercial aircraft and some military aircraft. The fatigue test matrix was defined to assess the impact of HVOF coatings on the fatigue life of the substrate.

The evaluation of fatigue in a coated part is really the analysis of how the coating affects the known values of an uncoated component. Baseline data for the alloys used in most applications already have been established. There are established methods and

specifications for determining fatigue properties. However, with coatings now applied, some of the guidelines used for bulk materials are somewhat different.

For most chrome-replacement testing, axial fatigue testing (ASTM E466-96) provides the most useful data for evaluation (rather than bend testing). In designing a fatigue testing protocol, some areas requiring definition are:

1. What is the load carrying capability of the coating and should this value be used in determining the applied stress? How will thickness of the coating affect this situation? The cross sectional area of the coating should be much less than that of the sample.
2. What is the best bar design for fatigue evaluation of coatings?
   - ☐ Hourglass (smoothly varying cross section, thinnest at the center)
   - ☐ Smooth section (constant cross section from some distance in center)
3. Will the testing mode be load (stress) or strain control?
4. Can grinding of the coating be repeatable on the fatigue bars to produce a consistent thickness and surface for testing?

As with all fatigue evaluations, considerations must be given to the following:

Frequency or speed of testing –will determine time for testing, but too high a frequency can cause overheating or a shift in results for strain rate sensitive materials

Type of control (load or strain) – will application of force to the bar be controlled purely by load or by the deformation induced in the part?

R ratio or A ratio – R ratio is defined as the ratio of minimum cyclic load to maximum cyclic load. For example, an R ratio of –1.0 means the maximum and minimum loads are the same but the loading is fully reversed from positive to negative. A ratio is defined as

(maximum stress - minimum stress)/(maximum stress + minimum stress)

Typical fatigue bar shapes are shown in Figure 3-7 and Figure 3-8. The most common designs are the hourglass (which can only be used for load-control fatigue), and the smooth bar. The hourglass bar was used for the bulk of the testing for consistency with existing data in the landing gear community. The hourglass shape is more sensitive to coatings and tends to give a wider separation of curves between coating conditions. Some tests with smooth bars were included to permit correlation with earlier HCAT generic testing. While for 0.003" coatings a small 0.25" diameter bar was used, for 0.010" coatings a 0.5" diameter bar was used to ensure that the bar cross section was much greater than that of the coating. Most testing was done at R=-1 (fully reversed), since that best corresponds with field conditions for military landing gear components. Some testing was done at R=0.1 (tension-tension) for comparison with earlier generic HCAT data and with Boeing test data.

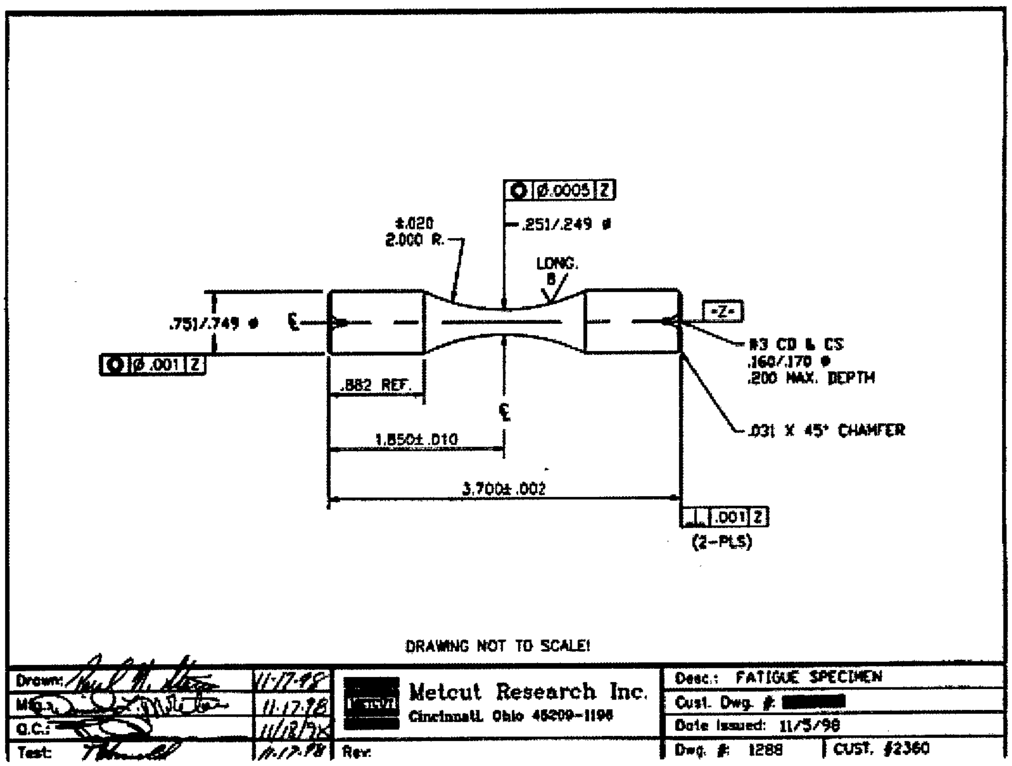


Figure 3-7. Typical Hourglass-shaped Fatigue Bar

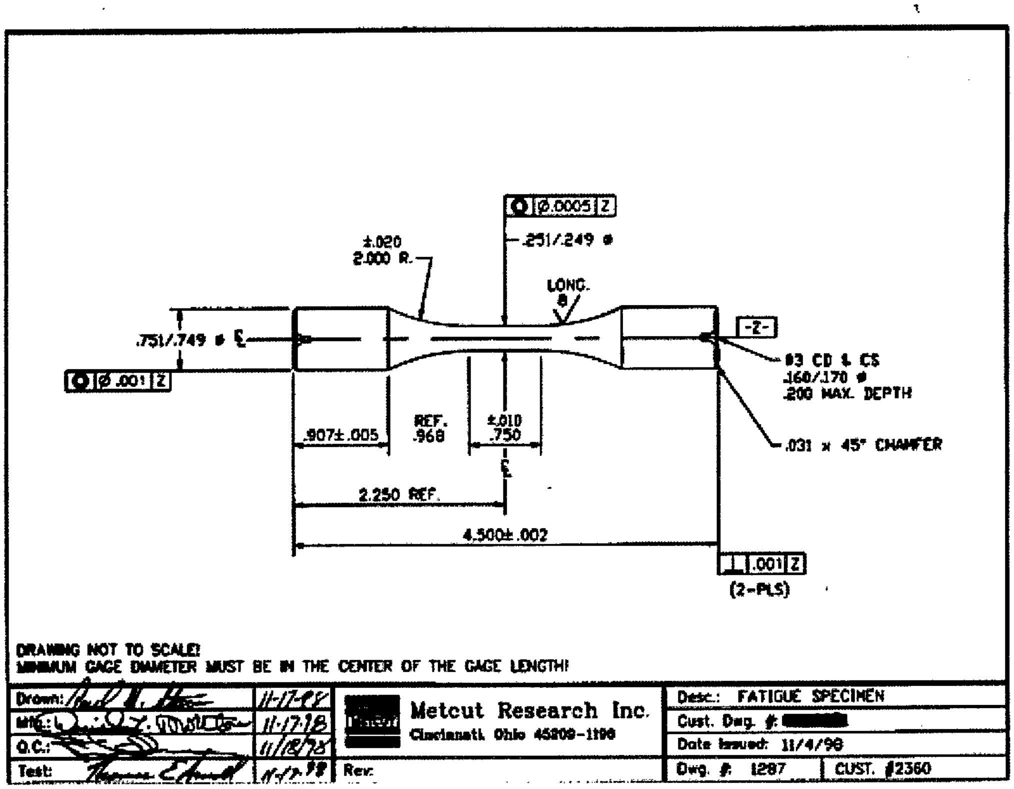


Figure 3-8. Typical Smooth Fatigue Bar

Fatigue testing for coating comparison must be defined by the important parameters of the spray process and the critical controls for consistent property evaluation as shown in Table 3-19.

Table 3-19. Fatigue Testing Variables

Coating/Substrate Information	Testing Information
Peening of substrate	Frequency of testing machine
Thickness of coating	Bar geometry
Surface finish (ground, unground, or superfinished)	Load vs. strain control
Location of coating (patch/full length)	R ratio, or A ratio
Almen (intrinsic stress) intensity	

Corrosion fatigue must also be a consideration, given the corrosive environments for many of the hard chrome applications. This usually involves the same considerations as testing in air but the test area in question is exposed to the corrosive media for the entire test or for specific periods of time. There may also be pre-exposures for the purpose of initiating corrosion followed by constant exposure to the environment in question. When defining the protocol for testing, the frequency of exposure, and the degree of replenishment must be stipulated to best approximate the actual service conditions.

3.3.3. Specimen Fabrication

3.3.3.1.Specimen Geometry and Materials:

In the case of the Landing Gear Joint Test Protocol (LG JTP), both configurations were selected for the fatigue evaluation.

- Hourglass: 0.25" gage diameter for specimens receiving 3-mil-thick coatings and 0.50" gage diameter for specimens receiving 0.010"-thick coatings (See Figure 3-7 and Figure 3-9).
- Smooth bar: 0.25" gage diameter over a gage length of 0.75" (See Figure 3-8)

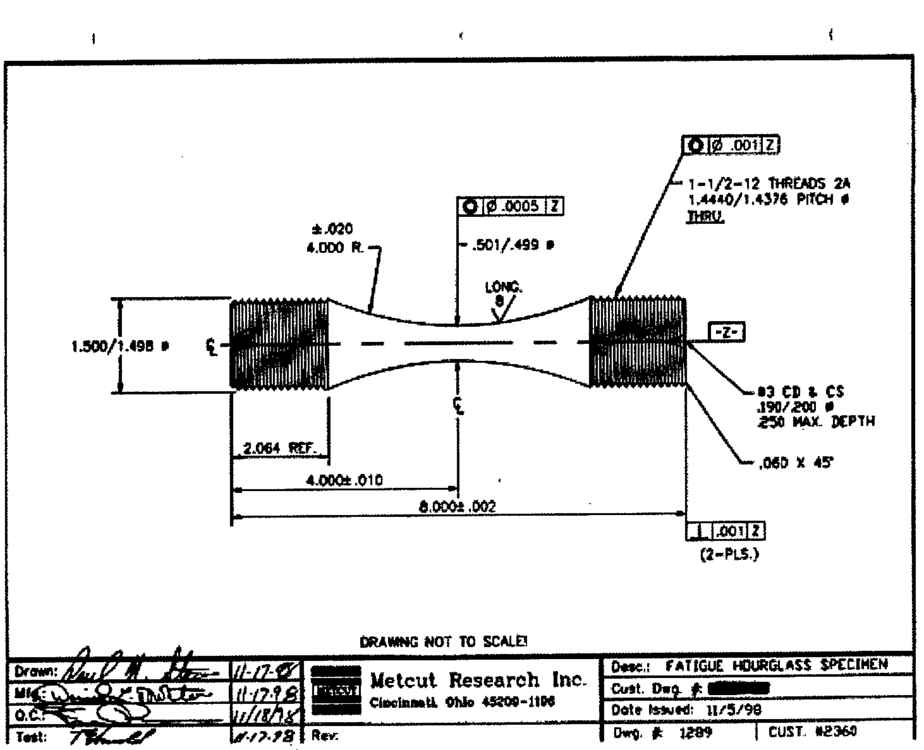


Figure 3-9. Hourglass Configuration with .500" Gage Section

The two smaller specimens (Figure 3-7 and Figure 3-8) were not threaded on the ends; rather, the smooth shank end was clamped in hydraulic grips. A threaded end was used for the larger hourglass specimen (Figure 3-9). The materials selected for the protocol are listed in Table 3-20.

Table 3-20. Substrate Materials in LG JTP

Material	Heat Treat (tens. Strength)	Shot Peen
4340	260-280 ksi	8-10A, S230, wrought steel
300M	280-300 ksi	8-10A, S230, wrought steel
Aermet 100	280-290 ksi	8-10A, S230, wrought steel

3.3.3.2. Specimen preparation

Specimen preparation involved four major steps: rough grinding, vacuum heat treatment, finish grinding/polishing, and shot peening.

The heat treat for the 4340 and 300M was in accordance with MIL-H-6875 and the heat treat for the Aermet 100 in accordance with P.S. 15169. When possible, all specimens were heat treated at same time. Grinding was performed to IAW MIL-STD-866 and

Metcut internal specifications (Table 3-21) as listed below. The fatigue specimen surface preparation involved low stress grinding followed by 600 grit alumina polishing which removed 0.001" minimum on all gage section surfaces in the polishing step of the specimens. Nital etching IAW MIL-STD-867 was conducted on all specimens to examine for grinding burns. All specimens were baked subsequent to Nital etching to remove residual hydrogen. All specimens to be tested (both coated and uncoated) were prepared in the same fashion to ensure a common starting condition prior to any surface preparation techniques used for the coatings. This approach was used to reduce fatigue test data scatter due to variations in the condition of the machined surfaces.

Where specified in the test matrix, shot peening was conducted to IAW AMS-2432 under computer control using the conditions specified in Table 3-20. The entire surface was shot peened to 100% surface coverage.

Table 3-21. Machining Procedures for Fatigue Specimens

Machining Procedures	
200.1.1	Specimen Preparation Procedure Low Stress Grind
Axial Polishing Procedures for Test Specimens	
200.4	Metcut Round Specimen Polish Procedures for All Materials

3.3.4. Coating deposition methodology

Fatigue specimens were coated with electroplated hard chrome and HVOF WC-17Co. The HVOF coatings were applied at Hitemco in Bethpage, NY. The hard chrome was applied at Ogden ALC (Hill AFB). All of the fatigue specimens were shot peened and solvent wiped with reagent grade acetone and or isopropyl alcohol prior to coating. All coatings were applied in a patch 0.5" long (0.75" long for 0.5" diameter bars) centered on the middle of the bar and feathered at the patch ends to limit stress concentrations. The coatings were deposited around the entire circumference to a thickness of 0.002 – 0.003" over the final diameter to allow for grinding after coating.

The fatigue specimens for hard chrome were prepared for plating by lightly hand abrading the areas to be coated with a Scotchbrite pad. Chrome plating was done at about 130 ^{0}F following MIL-STD-1501C, Class 1, Type 1. The resultant hard chrome was about 0.002" thicker than the final grind dimension and nominally 0.5" long, centered in the gage section of the fatigue specimen, and had feathered edges.

The fatigue specimens with HVOF WC-17Co were coated at Hitemco with a DJ 2600 system and Diamalloy 2205 agglomerated/sintered powder (nominal size, -270 mesh/+10 micron). They were prepared for coating by grit blasting with 24 grit aluminum oxide at 18-20 psi and then coated using the parameters given in Table 3-22. The smooth round bar and hourglass bar specimens were coated individually while rotating on axis and being traversed parallel to the length. A pair of shadow masks restricted coating deposition to the desired 0.5" region centered in the gage section and ensured proper feathering of the patch ends. Tape masking restricted grit blasting and the coating overspray area to a slightly wider area (0.6" max). Complete deposition conditions are

summarized in Table 3-22.

Table 3-22. DiamondJet 2600 Process Parameters for Deposition of WC-17Co

Equipment:	Model 2700 hybrid gun
Powder:	Diamalloy 2005 Powder Feed Rate: 8.5 lb/hr (325 rpm, 6 pitch feeder screw) Vibrator setting, 30 Powder Carrier Gas: Nitrogen pressure 148 psi Nitrogen flow 28 scfh Combustion Gas: Oxygen pressure 148 psi
Combustion fuel:	Hydrogen Fuel pressure – 135 psi console supply pressure Fuel flow rate – 1229 scfh
Combustion chamber Pressure:	100-102 psi
Gun Cooling Water Flow:	8.3-8.7 gph
Water Temperature to Gun:	In, 64- 72°F Out, 117-125 °F Delta, 51- 54 °F
Specimen Rotation:	2,636 rpm for round bars (0.25" dia.) – 16,560 in/min surface speed
Gun Traverse Speed:	400 linear in/min for round bars
Spray Distance	11.5"
Cooling Air:	2 gun mounted AJs at 14", 90-110 psi 1 stationary AJ at 4-6" pointed at coating area, 90-110 psi

3.3.5. Test methodology

Stress Levels : All fatigue tests were conducted in constant amplitude axial load-control in accordance with ASTM E466-96 to generate standard S-N curves (a plot of number of cycles to failure for given stress levels).

Maximum stress: approximately 180 ksi, in accord with Boeing fatigue test procedures

Stress direction: fully reversed (tensile/compressive, R=-1) for most

tests, some tests under tension-tension at R=0.1

Number of stress levels: 4

Number of specimens at each stress level: 5

Stress calculations: Calculated on as-machined diameters

Environments: The environments were: (1) Laboratory air at ambient temperature (2) 3.5% NaCl solution at ambient temperature. The procedure for conducting the corrosion fatigue tests was to immerse the entire fatigue specimen in a 3.5% NaCl solution for 24 hours. Then the specimen was removed, dried, stored in a desiccator for approximately 24-48 hours and then placed into the fatigue-testing machine in a cell (See Figure 3-10., Figure 3-11. and Figure 3-12. below) containing a 3.5% NaCl solution. The gage section of the fatigue specimen was immersed in the NaCl solution during the entire fatigue test. This cell was replenished with a constant flow of 3.5% NaCl solution during the test. The excess solution was not returned to the system.

The matrix for fatigue testing is indicated in Table 3-23.

Acceptance : After testing, the data were plotted in the standard manner with stress on the vertical axis and cycles-to-failure on the horizontal axis. A least squares regression was used to produce each S-N curve. The regression involved a linear fit to the data in ln (**N**) vs. ln (**σ**) space, then calculating a best fit curve in the traditional S-N space. If the curves for the HVOF coatings fell on or above the curves for the EHC, then the HVOF coatings were considered to have met the acceptance criteria.

The testing set-up is shown in Figure 3-10., Figure 3-11., and Figure 3-12.. These figures illustrate corrosion-fatigue testing, but the same arrangement was used for in-air testing (minus the stop-off paint and liquid receptacle).

Figure 3-10. Small (1/4" dia) Hourglass Bars for Corrosion Fatigue Testing

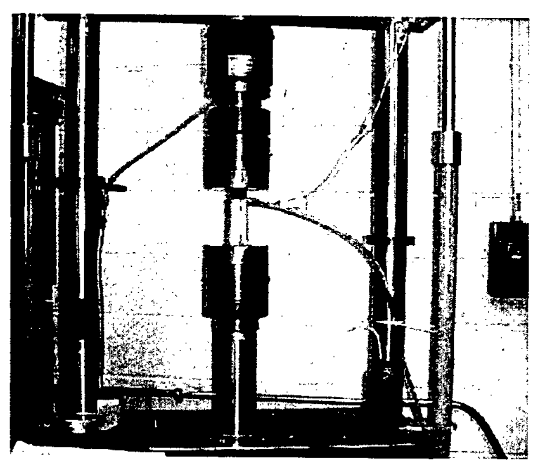


Figure 3-11. Corrosion Cell Set-up for Fatigue Testing: Large Hourglass

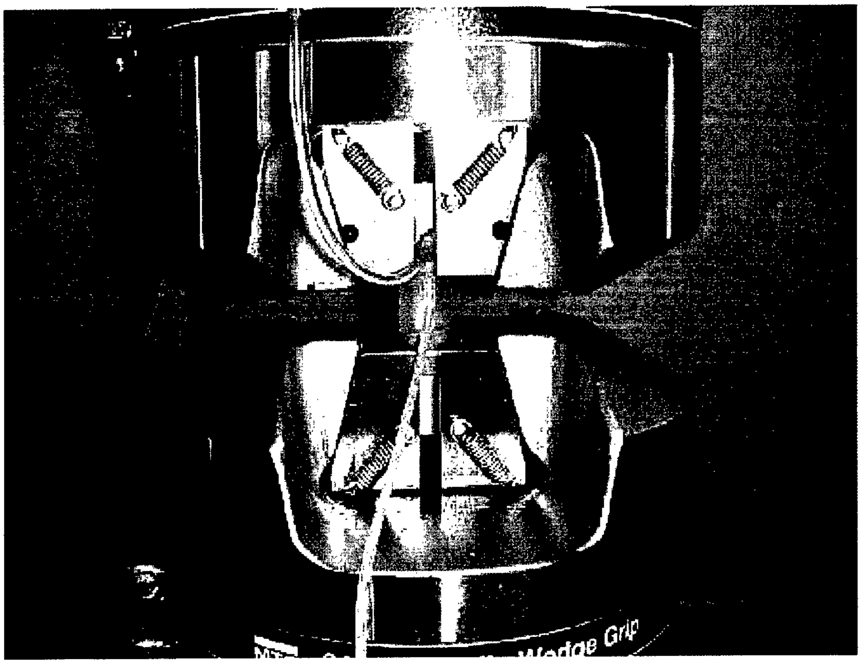


Figure 3-12. Close-up View of Corrosion Cell Set-up for Fatigue Testing: Small Hourglass Specimen

Table 3-23. Fatigue Test Matrix

Material	Geometry	Peen	Coating	Thickness (mil)	R	Environment	# of specimens
4340	Hourglass	No	WC-Co	3	-1	Air	20
4340	Hourglass	No	WC-Co	3	0.1	Air	20
4340	Hourglass	No	EHC	3	-1	Air	20
4340	Hourglass	No	EHC	3	0.1	Air	20
4340	Hourglass	Yes	EHC	3	-1	Air	20
4340	Hourglass	Yes	EHC	3	0.1	Air	20
4340	Hourglass	Yes	WC-Co	3	-1	Air	20
4340	Hourglass	Yes	WC-Co	3	0.1	Air	20
4340	Hourglass	Yes	WC-Co	10	-1	Air	20
4340	Hourglass	Yes	EHC	10	-1	Air	20
4340	Hourglass	Yes	EHC	3	-1	NaCl	20
4340	Hourglass	Yes	WC-Co	3	-1	NaCl	20
4340	Smooth bar	Yes	EHC	3	-1	Air	20

4340	Smooth bar	Yes	WC-Co	3	-1	Air	20
						Total	280

300M	Hourglass	No	Uncoated	3	-1	Air	20
300M	Hourglass	No	EHC	3	-1	Air	20
300M	Hourglass	No	WC-Co	3	-1	Air	20
300M	Hourglass	Yes	EHC	3	-1	Air	20
300M	Hourglass	Yes	WC-Co	3	-1	Air	20
300M	Hourglass	Yes	EHC	3	-1	NaCl	20
300M	Hourglass	Yes	WC-Co	3	-1	NaCl	20
300M	Hourglass	Yes	EHC	10	-1	NaCl	20
300M	Hourglass	Yes	WC-Co	10	-1	NaCl	20
300M	Smooth bar	Yes	EHC	3	-1	Air	20
300M	Smooth bar	Yes	WC-Co	3	-1	Air	20
						Total	220
Aermet 100	Hourglass	No	Uncoated	3	-1	Air	20
Aermet 100	Hourglass	No	EHC	3	-1	Air	20
Aermet 100	Hourglass	No	WC-Co	3	-1	Air	20
Aermet 100	Hourglass	Yes	EHC	3	-1	Air	20
Aermet 100	Hourglass	Yes	WC-Co	3	-1	Air	20
Aermet 100	Hourglass	Yes	EHC	3	-1	NaCl	20
Aermet 100	Hourglass	Yes	WC-Co	3	-1	NaCl	20
Aermet 100	Hourglass	Yes	EHC	10	-1	NaCl	20
Aermet 100	Hourglass	Yes	WC-Co	10	-1	NaCl	20
Aermet 100	Smooth bar	Yes	EHC	3	-1	Air	20
Aermet 100	Smooth bar	Yes	WC-Co	3	-1	Air	20
						Total	220
						Grand Total	720

3.3.6. Test results

The US Landing Gear JTP concentrated on fatigue of WC-Co coatings at both a .003" and .010" thickness. Substrate materials were 4340, 300M and Aeromet 100.

The JTP made primary comparisons between the following variables:

Coating: EHC vs WC-Co

Peening: Peened vs. unpeened

Configuration: Hourglass vs. smooth

Environment: Air vs. NaCl

Thickness: .003" vs. .010"

The primary goal of this program was to generate comparative S-N curves to assess fatigue performance. The issues of coating integrity (cracking/spalling) were not anticipated by the JTP, and the issue did not arise until the US JTP fatigue testing was almost complete. Consequently, no provision was made in the test plan to carefully monitor coating behavior during each test. For this reason, observations regarding coating integrity reported herein were limited to post-test assessments only.

3.3.6.1. 4340 Substrate

The comparisons as outlined above were made for the 4340 substrate material. The bar configuration comparison was included in the protocol to provide a link to earlier work performed on the smooth configuration. An additional comparison of R ratios was also made for this same reason.

General comments on the comparisons are:

- Figure 3-13. shows the comparison of unpened vs. peened data. While, as expected, peening significantly raised the EHC curves, it made little difference to the HVOF data. The hourglass configuration is quite sensitive in differentiating chrome vs. HVOF in the unpeened condition.
- Figure 3-14. shows the comparison of bar configurations. As experienced in other protocols, the smooth bar configuration moves the curve to the left or shorter fatigue lives. However, in contrast to previous observations, the spread between chrome and HVOF is not substantially different.
- Figure 3-15. shows the comparison of environments, namely air vs. NaCl. The NaCl curves show roughly equal degradation in fatigue performance between chrome and HVOF.
- Figure 3-16. shows the comparison between the .003" and .010" coatings. Due to the .010" coating thickness, this data not only represents a thicker deposit but also a larger diameter bar. Since the bar diameters are different, the comparison can be somewhat skewed since larger diameter bars sometimes show reduced fatigue performance. It is therefore uncertain if the fatigue reduction is due primarily to the thicker coating or to the sample diameter.

❑ Figure 3-17. shows the comparison of R ratio, namely -1 and 0.1 values. As expected, the R = -1 curve (solid) is shifted down and to the left (i.e. R=-1 is a more severe fatigue condition) of the R=0.1 (dotted). However, surprisingly, the R=0.1 data show a much larger spread between chrome and HVOF than the R=-1 data.

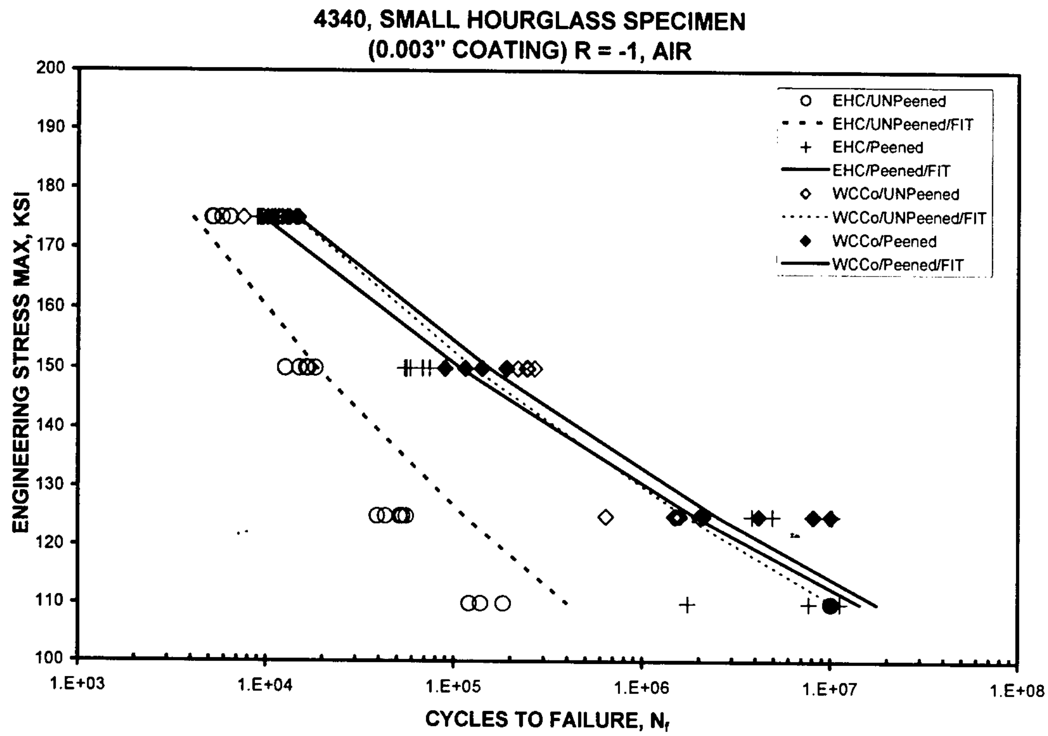


Figure 3-13. 4340 Fatigue - Hourglass Configuration, Air Environment, R = -1

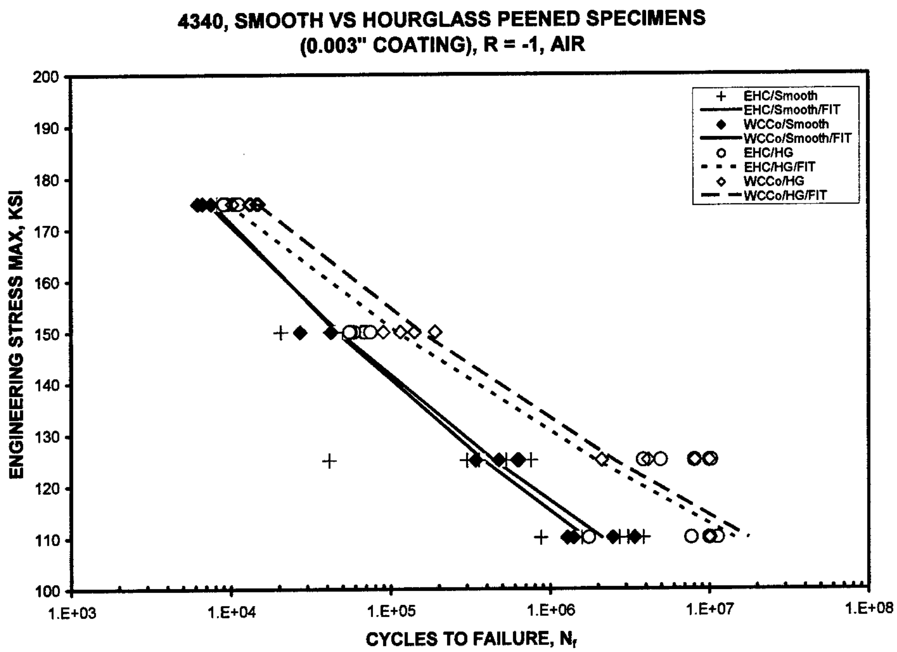


Figure 3-14. 4340 - Hourglass vs. Smooth Bar Configuration in Air Environment , R = -1

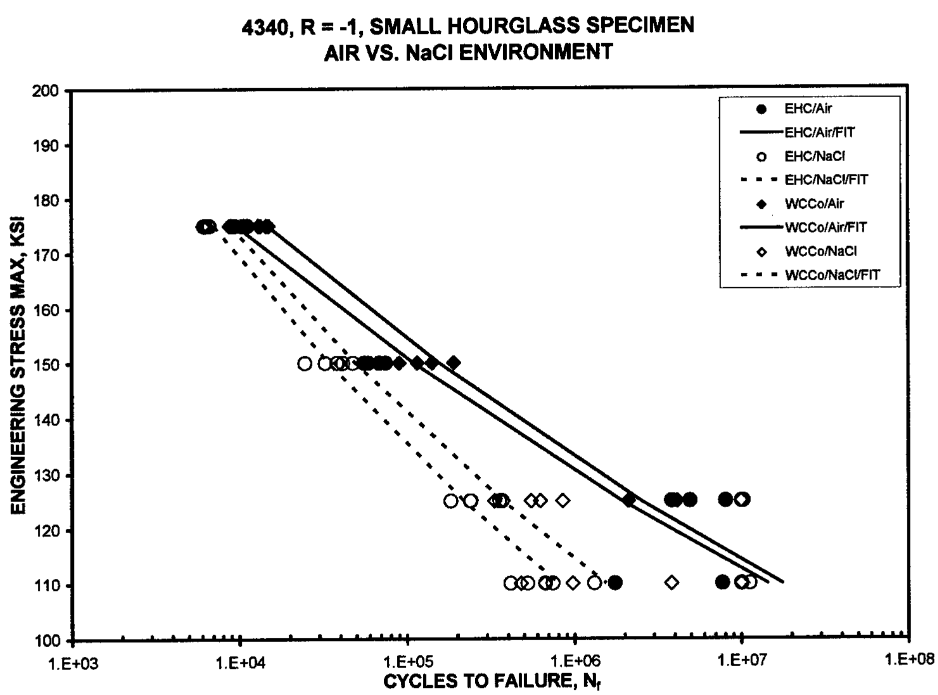


Figure 3-15. 4340 - Air vs. NaCl Environment Comparison, Hourglass Configuration, 0.003" Thickness, R = -1

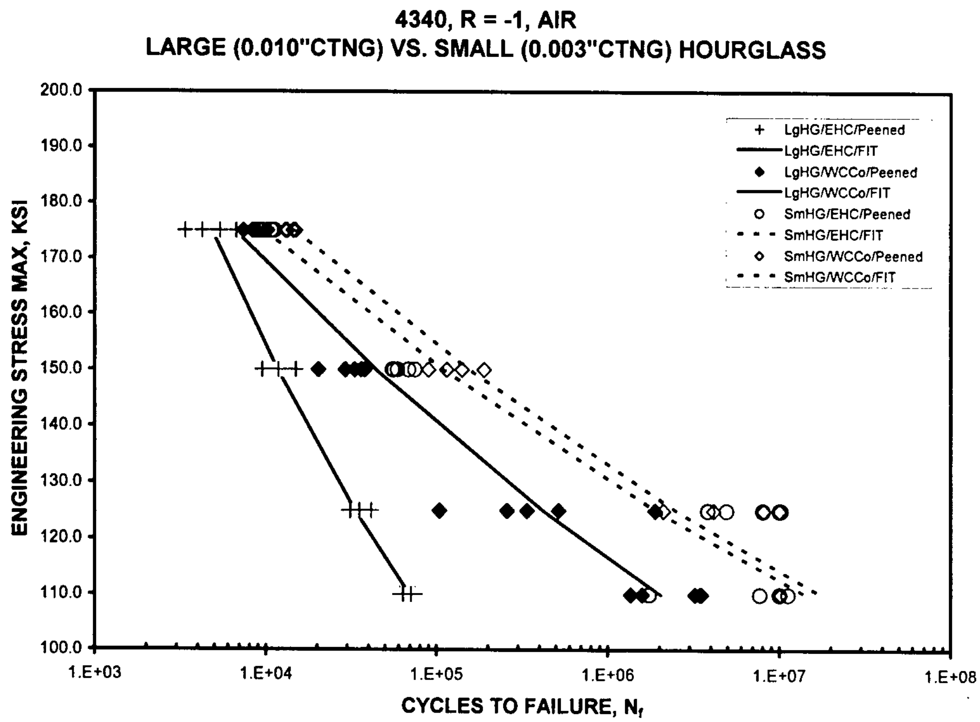


Figure 3-16. 4340 - 0.003" vs. 0.010" Thickness Comparison, Air Environment, Hourglass Configuration, R=-1, on 0.250" and 0.500" Specimens, Respectively

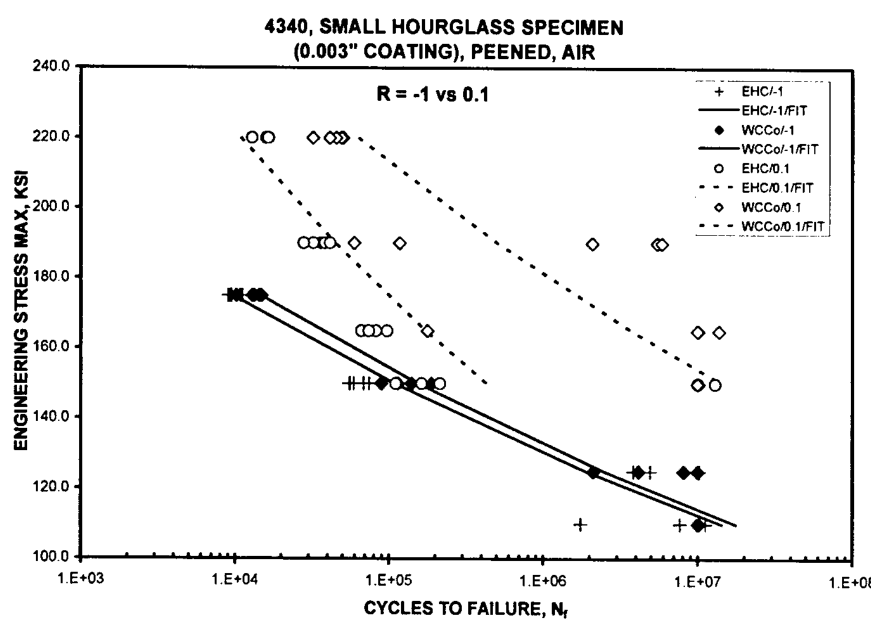


Figure 3-17. 4340 – R Ratio Comparison, Hourglass Configuration, 0.003" Thickness

3.3.6.2. A100 substrate

Similar comparisons were made for the A100 substrate material.

General comments on the comparisons are:

- Figure 3-18. shows the comparison of unpeened vs. peened data. As compared to 4340, there appears to be a stronger differentiation between chrome and HVOF. Again, the hourglass configuration appears to show more sensitivity in differentiating chrome vs. HVOF in the unpeened condition, but there is in this case a wider spread between the unpeened and peened material.
- Figure 3-19. shows the comparison of bar configurations. As with the other materials, the HVOF hourglass performance is better than the smooth configuration. Again, as with previous protocol observations, the spread between chrome and HVOF is bigger for the hourglass configuration.
- Figure 3-20. shows the comparison of environments, namely air vs. NaCl. As expected, the NaCl curves show a degradation in fatigue performance, and the difference between chrome and HVOF is essentially equal to that in air.
- Figure 3-21. shows the comparison between the .003" and .010" coatings in an NaCl environment. Due to the .010" coating thickness, these data not only represent a thicker deposit but also a larger diameter bar. Since the bar diameters are different, the comparison can be somewhat skewed since larger diameter bars sometimes show reduced fatigue performance, as noted above. We cannot therefore separate the effects of bar diameter and coating thickness. However, the general trends for either thickness value are similar in comparing chrome with HVOF. We can conclude that a thicker coating does not provide significantly better corrosion protection than the thinner one under fatigue conditions.

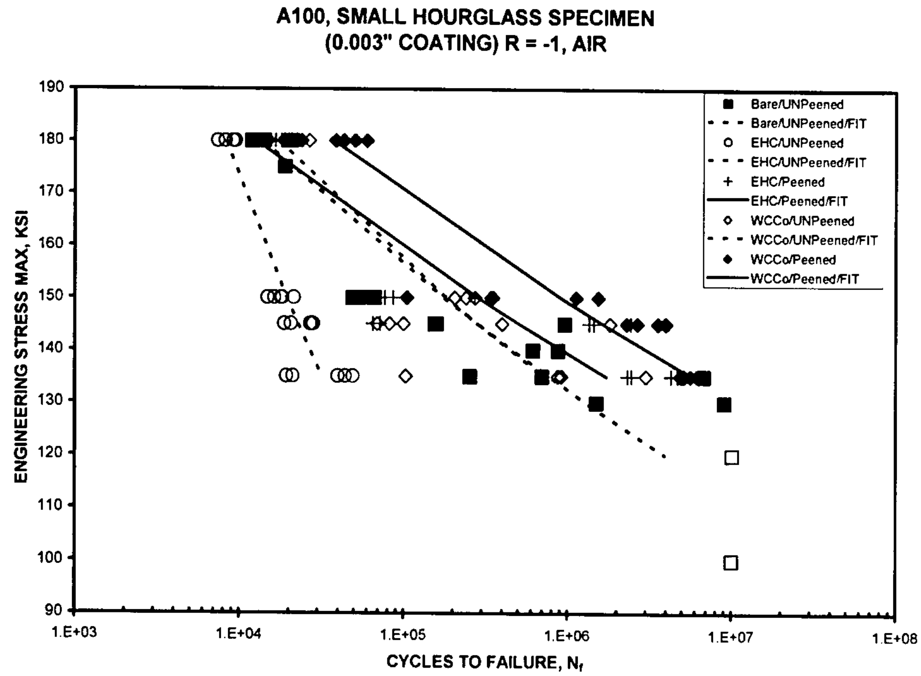


Figure 3-18. A100 - Unpeened vs. Peened Substrate Comparison, Hourglass Configuration, R= -1, 0.003" Thickness

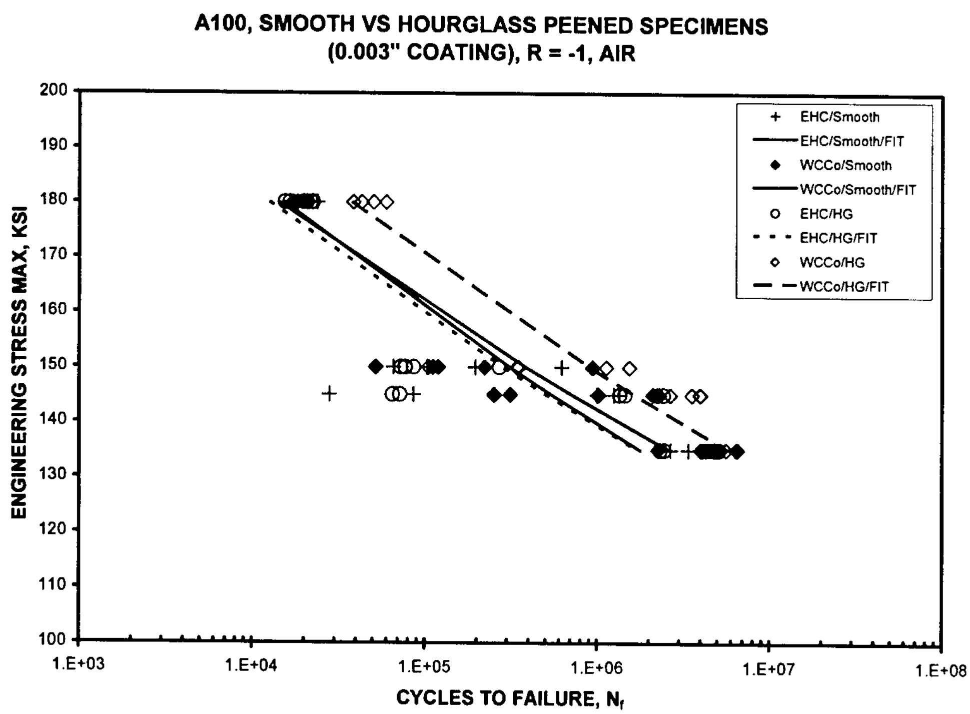


Figure 3-19. A100 – R= -1 vs. R=0.1 Comparison, Hourglass Configuration, 0.003" Thickness

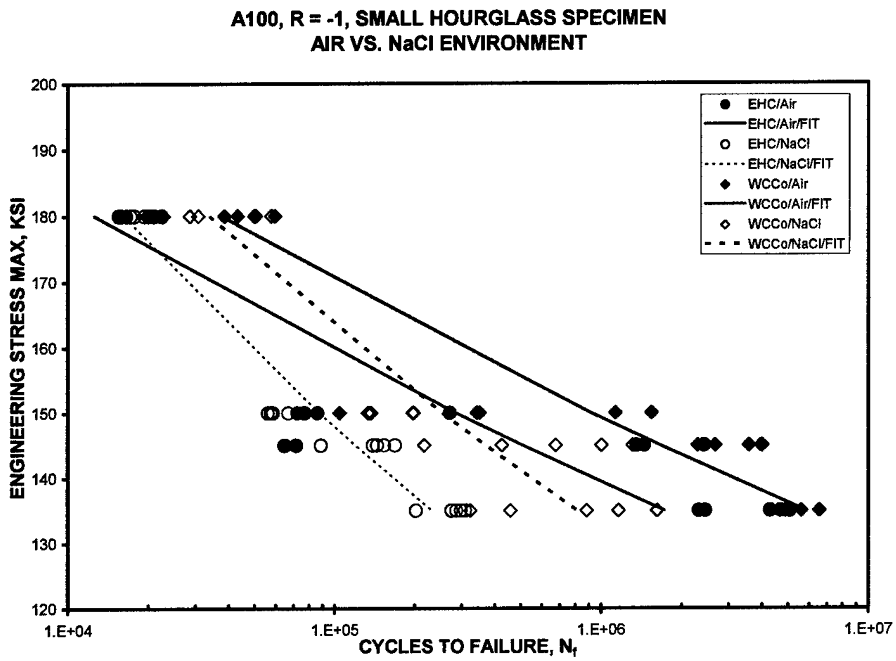


Figure 3-20. A100 – Air vs. NaCl Environment Comparison, Hourglass Configuration, R = -1

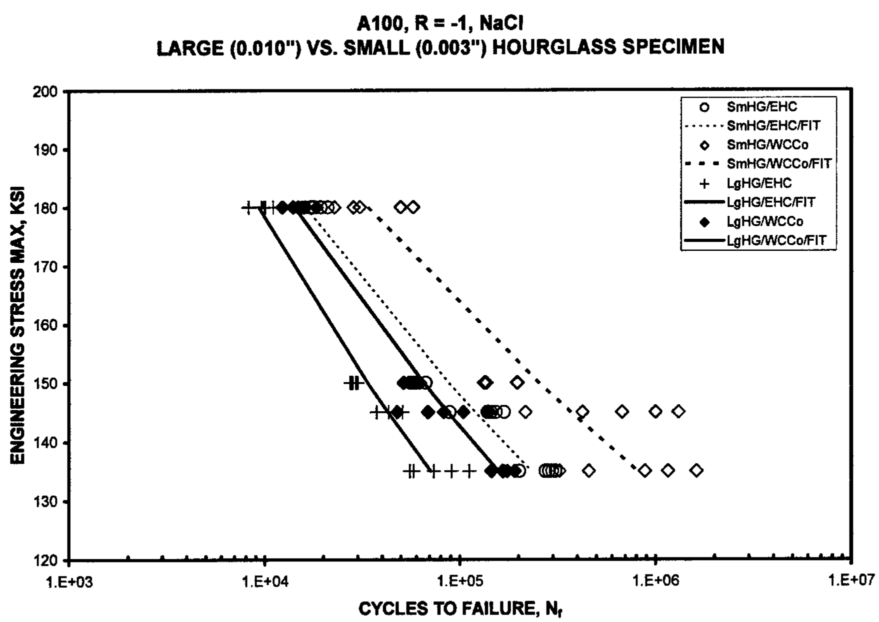


Figure 3-21. A100 - .003" vs. .010" Thickness Comparison, Hourglass Configuration, NaCl Environment, R= -1, 0.250" and 0.500" Diameter Bars, Respectively

3.3.6.3.300M substrate

General comments on the comparisons for 300M are:

- Figure 3-22. shows the comparison of unpeened vs. peened data. As with 4340, there is little differentiation between chrome and HVOF in the peened condition and the unpeened HVOF is identical to the two peened conditions. Unpeened EHC is substantially lower, as expected, and is little different from the unpeened, uncoated baseline. Again, the hourglass configuration appears to show more sensitivity in differentiating chrome vs. HVOF in the unpeened condition.
- Figure 3-23. shows the comparison of bar configurations. In contrast to the 4340, the hourglass and smooth performance is almost identical.
- Figure 3-24. shows the comparison between the .003" and .010" coatings in an NaCl environment. As before, we cannot separate the effects of coating thickness and bar diameter.
- Figure 3-25. shows the comparison of environments, namely air vs. NaCl. As expected, the NaCl curves show a degradation in fatigue performance but the differences between chrome and HVOF are essentially equal to those in air.
- There is no measurable difference between EHC and WC-Co.

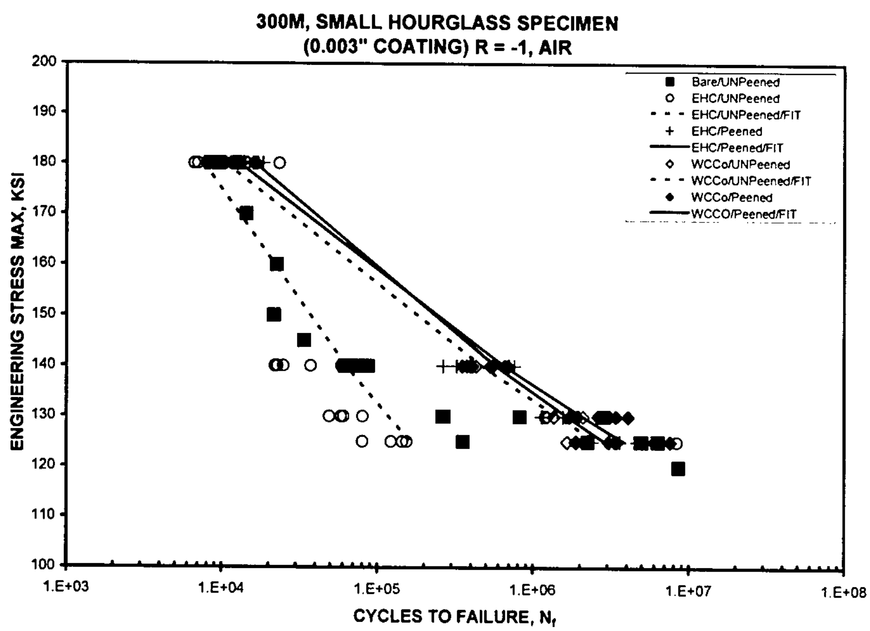


Figure 3-22. 300M - Peened vs. Unpeened Substrate Comparison, Hourglass Configuration, 0.003" Thickness, R= -1

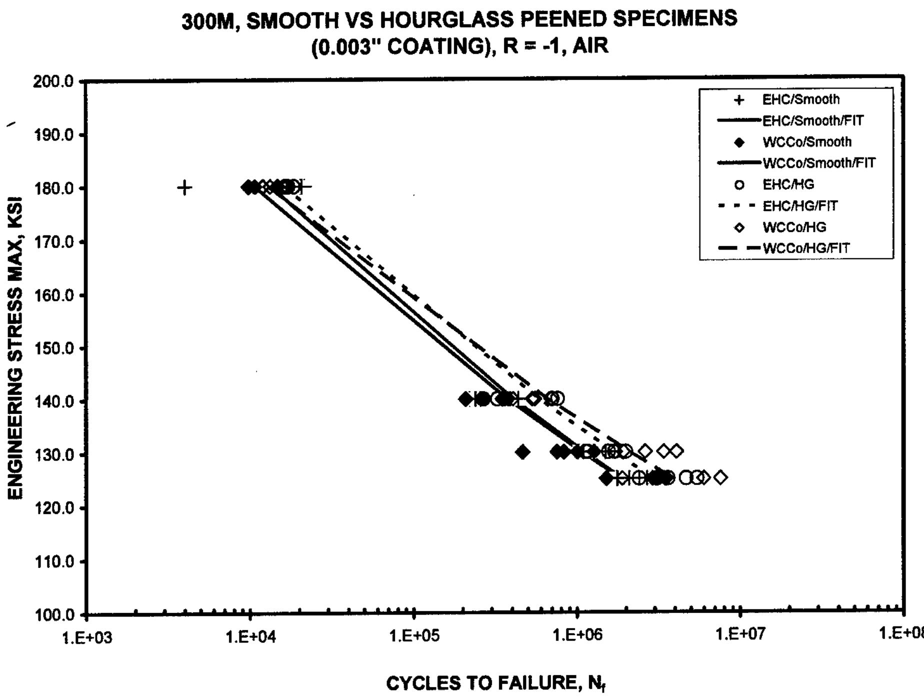


Figure 3-23. 300M – Smooth Bar vs. Hourglass Bar Comparison, 0.003" Thickness, R= -1

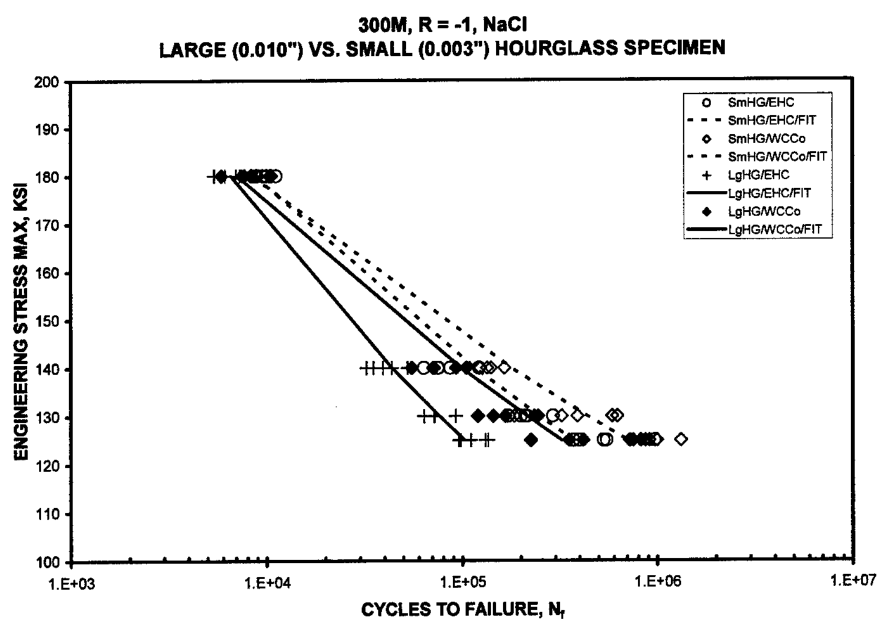


Figure 3-24. 300M - 0.010" Thick Coating on 0.500" dia Hourglass vs. 0.003" Thickness, 0.250" dia Hourglass, R= -1

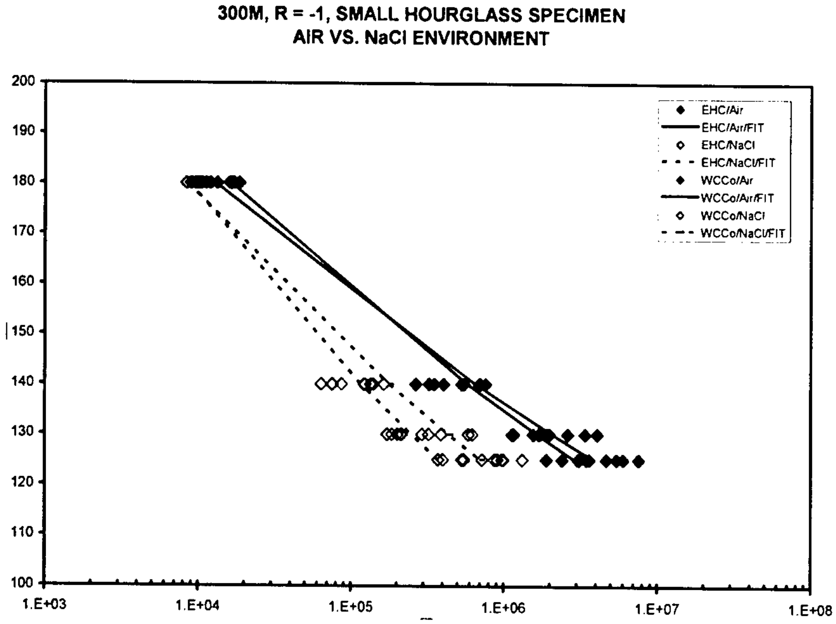


Figure 3-25. 300M - Air vs. NaCl Environment, Hourglass, 0.003" Thickness, R= -1

3.3.7. Coating integrity

As noted above, the coating integrity analysis (cracking and spalling) performed in this testing was primarily post-test since this issue was highlighted as a major concern only as the final bars were being finished in the protocol.

Cracking of the coating as shown in Figure 3-26 was observed on all bars essentially at or above the 150 ksi stress level. Spalling behavior is summarized in Table 3-24. For the small hourglass configuration and the .003" thickness, the majority of the bars showed spalling of the HVOF coating ***only*** near the fracture plane, and only ***after*** fracture, as depicted in Figure 3-27. However, in some cases there was total spalling on fracture, as shown in Figure 3-28, which was especially evident for 0.003" WC-Co on the A100 substrate material.

For the large hourglass specimens with the .010" coating, spalling was not observed prior to failure, but total spalling occurred on all specimens at failure regardless of the substrate type or test environment.

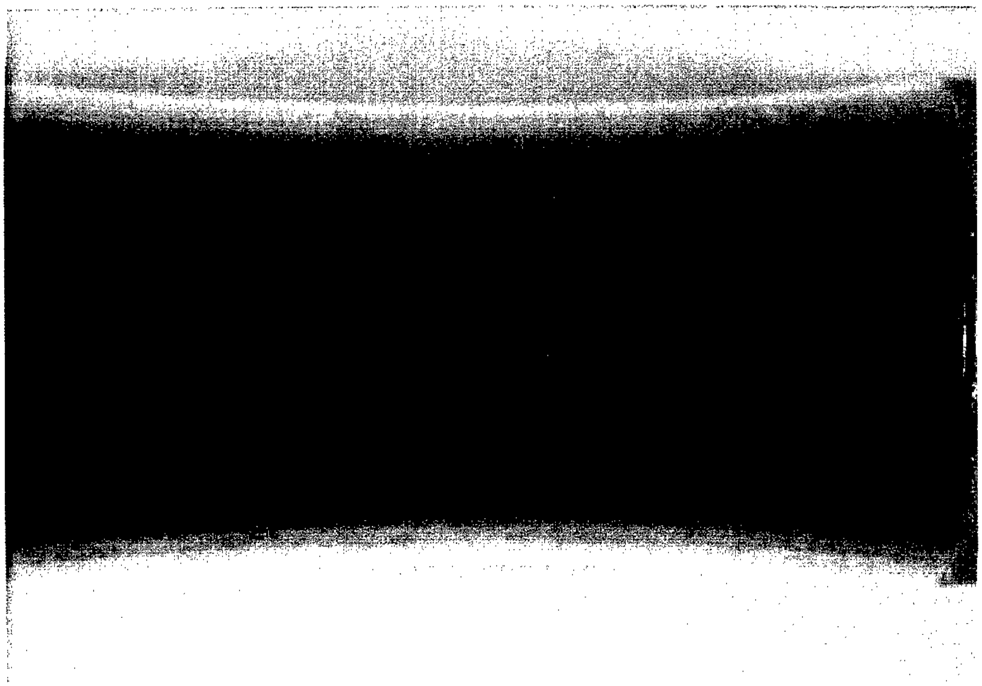


Figure 3-26. Cracking of HVOF Coating in Central Region of Hourglass Specimen

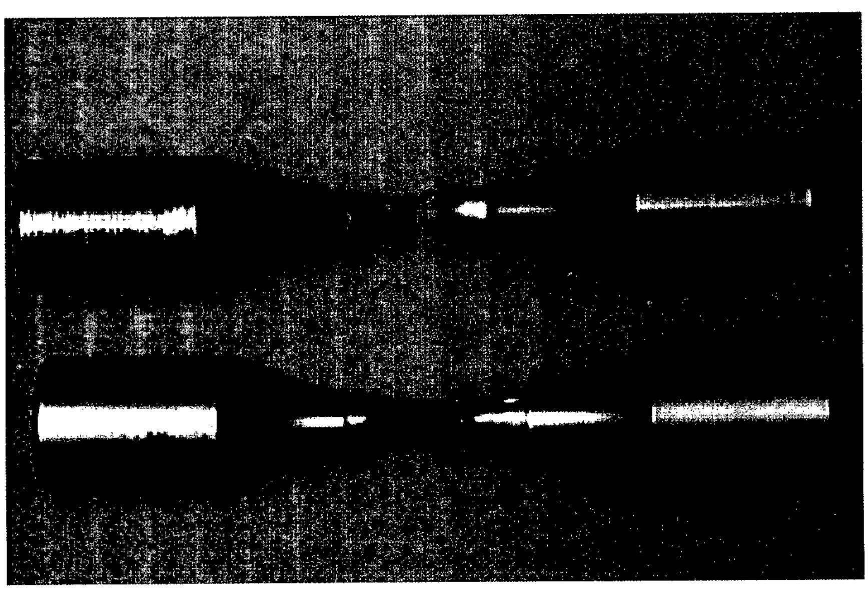


Figure 3-27. Failed 300M Specimens Showing Spalling in Small Zone Near Fracture Surface

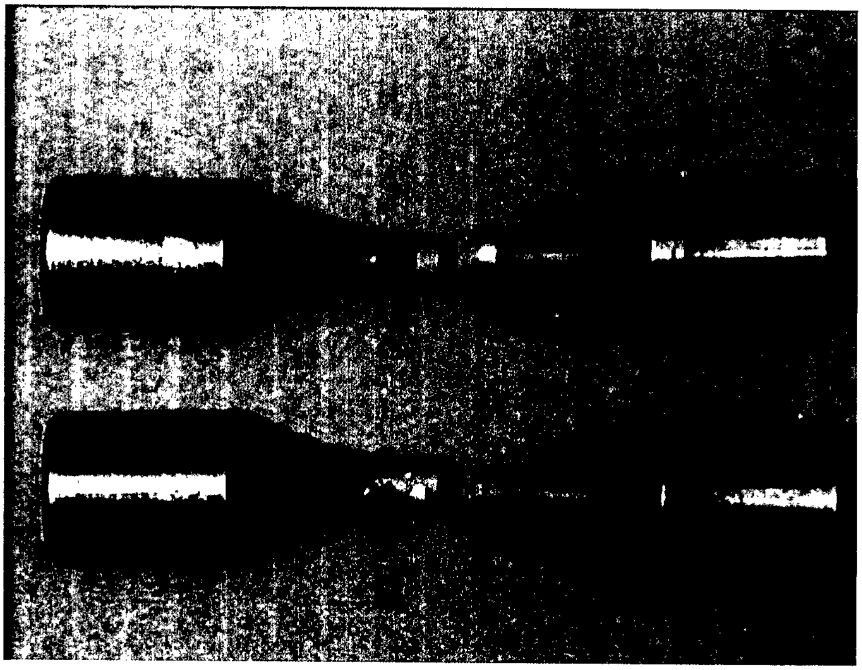


Figure 3-28. Failed 300M Specimens Showing Total Spallation on Fracture

Table 3-24. Coating Integrity - Summary of Analysis

R	Environment	Coating	Appearance at fracture	Appearance at runout
0.1	Air	EHC (4340 only)	No spalling. No apparent difference between peened and unpeened bars.	No spalling. No apparent difference between peened and unpeened bars.
		WC-Co (4340 only).	Spalling near fracture plane on all specimens. No completely spalled bars.	Little/no evidence of cracking or spalling.
-1	Air	EHC	No spalling. No apparent difference between peened and unpeened bars.	No spalling. No apparent difference between peened and unpeened bars.
		WC-Co	Spalling near fracture plane. Total spalling: 4340 – 0/20 peened & unpeened 300M – 4/20 peened, 2/20 unpeened A100 – 13/20 peened, 0/20 unpeened	Cracking/multicracking present. Occasional spalling evident. (4340) No run-outs for 300M or A100
-1	NaCl	EHC	No spalling	N/A
		WC-Co	4340: Spalling near fracture plane on all bars 300M: 14/20 bars not spalled A100: Spalling on all bars, 1/20 completely spalled	N/A

3.3.8. Discussion of trends in fatigue results

The following are general trends:

- In all cases HVOF fatigue performance was equal to (and in many cases better than) chrome.
- The fatigue performance of smaller specimens with 0.003" coatings was better than that for the larger specimens with the 0.010" coatings in both air and NaCl test environments. However, since different bar diameters can also affect fatigue life, we cannot confidently ascribe this effect to coating thickness.
- Fatigue life was significantly lower for R= -1 than for R= 0.1, as would be expected for full stress reversal.

- Surprisingly, there was little difference in hourglass vs. smooth configurations, in contrast to earlier protocols where the hourglass showed a more substantial degradation with chrome as compared to HVOF. The differences between smooth and hourglass configurations appear to be accentuated at R= 0.1, and are less evident at R= -1, where most of the JTP testing was done.
- While many HVOF coatings spalled on fracture, only limited cases of spalling were observed on runout specimens (i.e. specimens that had not failed). This was true for both hourglass and smooth bars. Macroscopic cracking of the HVOF coating was evident in some of the runout bars at R= -1, but only microcracking was observed at R= 0.1.
- If cracking of the HVOF coating did occur during testing in NaCl, it did not degrade fatigue performance as compared to chrome.

Shot peening: Because of the known fatigue debit for hard chrome, high strength steels are always required to be peened prior to coating. This causes a very large improvement in fatigue performance. Note, however, that the improvement in performance for unpeened HVOF over unpeened chrome is generally quite large, whereas for peened steels the difference is much less pronounced (see, Figure 3-13. for example). The reason for this is believed to be that the hard WC particles in the HVOF spray have the effect of shot peening the surface of the steel at the beginning of coating deposition and then shot peening the surface of the coating as it becomes thicker. This results in improved fatigue performance of the substrate and higher compressive stress in the coatings. It is important to remember that this peening effect is expected to be much less important when depositing alloys such as T400, where the spray does not include hard, unmelted particles.

3.3.9. Significance

Military landing gear components obviously are subjected to both static and cyclic loading. As the aircraft move from land-based to carrier-based situations, environmental factors can influence performance. The fatigue testing is significant in establishing that HVOF coatings do not degrade substrate fatigue, with or without corrosion.

However, the data established in this protocol and subsequent evaluations have identified the need for coating integrity (cracking and spalling) measurements to optimize coating performance and establish the load-limiting factors. From initial additional testing, coating integrity appears to be a concern primarily for thick coatings (i.e. for repair), and of much less concern for thin (OEM) coatings. Further evaluations are in progress and are planned to accurately establish this performance characteristic, and the results will be presented in a subsequent report.

3.3.10. Conclusions

The WC-Co coatings meet the JTP acceptance criterion of fatigue performance equal to or better than chrome plating in both air and NaCl environments. This conclusion is true for both .003" and .010" thicknesses.

The issue of coating integrity (cracking and spalling) has been identified and is being addressed in parallel programs to establish application and load ranges for HVOF coatings.

3.4. Corrosion data

3.4.1. Data summary

Table 3-25. Quick Data Locator (Click on item number to view)

Item	Item number
Test matrix	Table 3-31
JTP data – protection ratings on 4340	Figure 3-35, Figure 3-36
JTP data – protection ratings on 300M	Figure 3-41, Figure 3-42
JTP data – protection ratings on Aermet 100	Figure 3-44, Figure 3-45
Supplementary data – Comparison of appearance and protection ratings on 4340 plate	Figure 3-54
Supplementary data – Appearance ratings for 4340 rod	Figure 3-55
Supplementary data – Protection ratings for 4340 rod	Figure 3-57
Supplementary data – Appearance ratings for 300M rod	Figure 3-56
Supplementary data – Protection ratings for 300M rod	Figure 3-58

3.4.2. Pre-JTP atmospheric corrosion testing

As discussed in the Introduction to this report, some generic fatigue and corrosion testing were conducted prior to the initiation of the landing gear project [3.2]. ASTM B117 salt fog testing and atmospheric corrosion testing were conducted on flat panels of 4340 steel, 7075 aluminum alloy, and PH13-8 stainless steel coated with HVOF WC-Co (83%/17%), HVOF Tribaloy 400 (composition 60%Co, 28%Mo, 9%Cr, and 3%Si), and EHC. Coating thickness was nominally 0.004 inches. The results of the B117 testing after 1000 hours of exposure indicated that the WC-Co and EHC demonstrated equivalent performance, with the Tribaloy 400 demonstrating slightly inferior performance [3.2, 3.3]. Although it was intended that this JTR would report results only for those tests delineated in the Landing Gear JTP, because the corrosion results were inconsistent between the earlier generic testing and that conducted under the JTP, it was decided that the results of the atmospheric corrosion tests just for the same substrate material as used in the JTP would also be presented in this report. The deposition parameters used for the coatings in the earlier atmospheric corrosion studies were very similar to those used in

the tests for the JTP.

3.4.2.1. Specimen preparation

Samples of 4340 steel (dimensions 4" x 6" x 0.2" thick) were obtained from commercial sources. Prior to deposition of the coatings, the samples were degreased and then grit blasted with 180 - 220 grit aluminum oxide for those to receive EHC and with 54 grit aluminum oxide for those to receive the HVOF coatings. The angle of impingement was 90 degrees.

- ❑ EHC was applied to samples in accordance with United States military standard MIL-STD-1501.
- ❑ The 83WC/17Co coatings were deposited at the Naval Aviation Depot in Jacksonville, Florida using a Sulzer Metco Diamondjet hybrid HVOF system with hydrogen as the fuel gas. The 83WC/17Co powder material was Sulzer-Metco Diamalloy 2005 with a composition of 83% WC and 17% Co.
- ❑ The Tribaloy 400 coatings were deposited at Southwest Aeroservice, Inc. in Tulsa, Oklahoma using a Stellite Jet Kote II HVOF system with hydrogen as the fuel gas. The Tribaloy 400 powder material was designated as T400 and was manufactured by Stellite with a composition of 60% Co, 28% Mo, 9% Cr, 3% Si.

All of the HVOF coatings were deposited such that they retained residual compressive stress as indicated on an Almen N strip, with deflections ranging from 0.005" to 0.010". The porosity was less than 1.5% and the oxide content was less than 2.5%. The average Vickers microhardness for the coatings (100 gram load) was 950 for the EHC, 1150 for the WC-17Co, and 700 for the T400. The nominal thickness for all of the coatings was 0.004".

All of the coatings were tested in the as-deposited condition, with no surface finishing or grinding conducted subsequent to deposition. At least five samples were produced for each coating/substrate combination. The T400 coatings covered the entire sample including the edges. For the EHC, the coatings were applied to an area of 4" x 4 ", with both faces and edges within that area being coated. For the WC-17Co on the 4340 substrates, the coatings were applied to one face and the edges but not the reverse face. For all samples, any uncoated areas were sealed using epoxy.

The samples were placed in the atmospheric exposure rack at the Naval Research Laboratory facility in Key West, FL. The exposure racks were located approximately 50 yards from the ocean, with the samples facing the ocean at an angle of 45 degrees from the horizontal. The test duration was three years.

3.4.2.2. Experimental Procedures

After exposure, the samples were cleaned in accordance with ASTM B537. After the corrosion products were removed, blisters and undercutting of the coating were noted. The blisters and undercut coating were mechanically removed to better assess the extent of the corrosion, i.e., determine the area of the substrate that was no longer protected by the coating. Then each sample was assigned a protection rating based on the ASTM B537 standard, which is summarized in Table 3-26. This standard only considers the face of the samples for rating, but in this work the sample edges were also assigned a protection rating. The protection rating is an indication of how well the coating protected the substrate.

Table 3-26. Protection Rating Versus Area of Defect from ASTM B 537

Area of defect (%)	Rating
0	10
0 to 0.1	9
0.1 to 0.25	8
0.25 to 0.5	7
0.5 to 1.0	6
1.0 to 2.5	5
2.5 to 5.0	4
5 to 10	3
10 to 25	2
25 to 50	1
greater than 50	0

3.4.2.3. Results and Discussion

Figure 3-29 and Figure 3-30 show a series of photos taken before and after cleaning, respectively, of the coatings on 4340 steel after the three-year atmospheric exposure. Once the samples were cleaned, it was possible to identify surface defects such as blisters or pits. Removing the blisters and portions of the coating that were undercut by corrosion provided a better representation of the affected areas as shown in Figure 3-30. This surface condition was used to determine the protection ratings for the front face and edges.

Table 3-28 and Figure 3-31 present the protection ratings for the coatings on 4340 steel. The front face of all samples coated with T400 showed significant undercutting, with the percentage of the surface affected ranging from 10 to 50. The protection ratings for the face of individual samples ranged from 1 to 3, with an average of 1.9. For the edges, greater than 50% were corroded with a significant amount of undercutting of the coating. The average protection rating for the edges was 0. The T400 samples were very heavily corroded near the edges and it appeared that the undercutting started at the edges and moved toward the center of the face.

The front face of all EHC samples showed that the coating was severely undercut similar to the T400. The protection ratings for individual samples ranged from 0 to 2, with an average of 0.5. The edges were also heavily corroded with significant undercutting. The average protection rating was 0.2 for the edges with the individual values ranging from 0 to 1.

The face and edges of the WC-17Co samples showed no sign of corrosion. The protection rating for the individual samples, both the front face and edges, was 10. In general, the surface of the WC-17Co coatings became darker in color during exposure. Upon cleaning the dark layer was removed and it was apparent that the coating itself had undergone some general corrosion. This was probably due to dissolution of the cobalt

binder. The HVOF WC-17Co coating clearly outperformed the EHC and HVOF T400 coatings in terms of providing protection to both the face and edges.

As mentioned above, the results of ASTM B117 testing of samples identical to those that were subjected to the atmospheric exposure were previously reported [3.2]. Table 3-27 provides a summary of the B117 results which were significantly different from the atmospheric corrosion results. In the B117 tests, both the WC-Co and EHC performed equivalently, with fairly extensive corrosion evident. Both had an average protection rating for the faces of about 3 after 1,000 hours exposure. The T400 had an average protection rating of 1.6. However, as discussed above, in the atmospheric corrosion tests, the HVOF WC-Co coating protected the steel significantly better than the other two coatings.

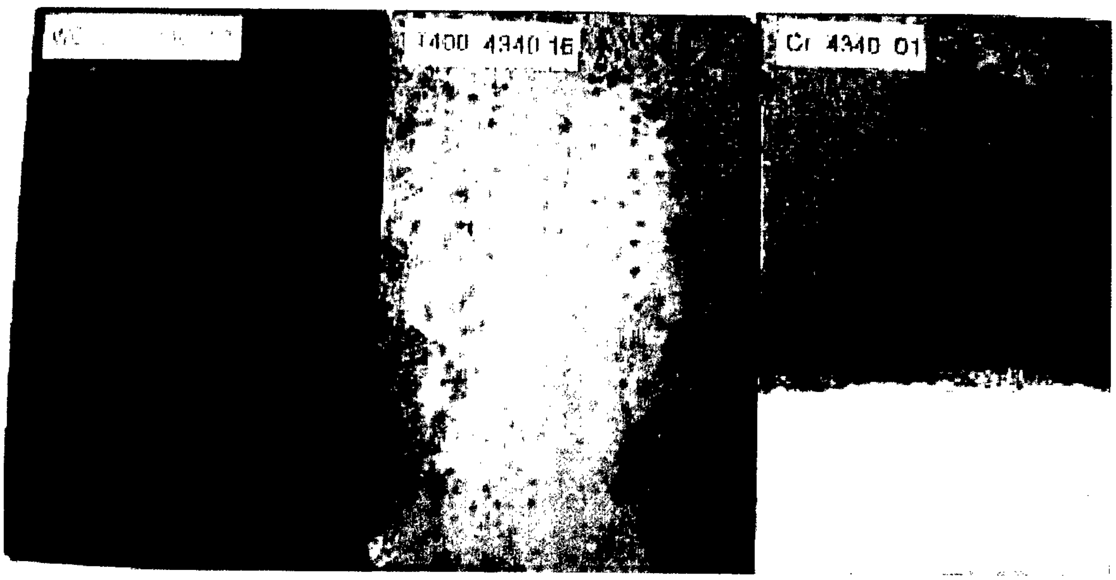


Figure 3-29. HVOF WC-Co, Tribaloy 400 (T400) and EHC (Cr) on 4340 Steel Following Three-year Atmospheric Exposure (Samples shown prior to cleaning)

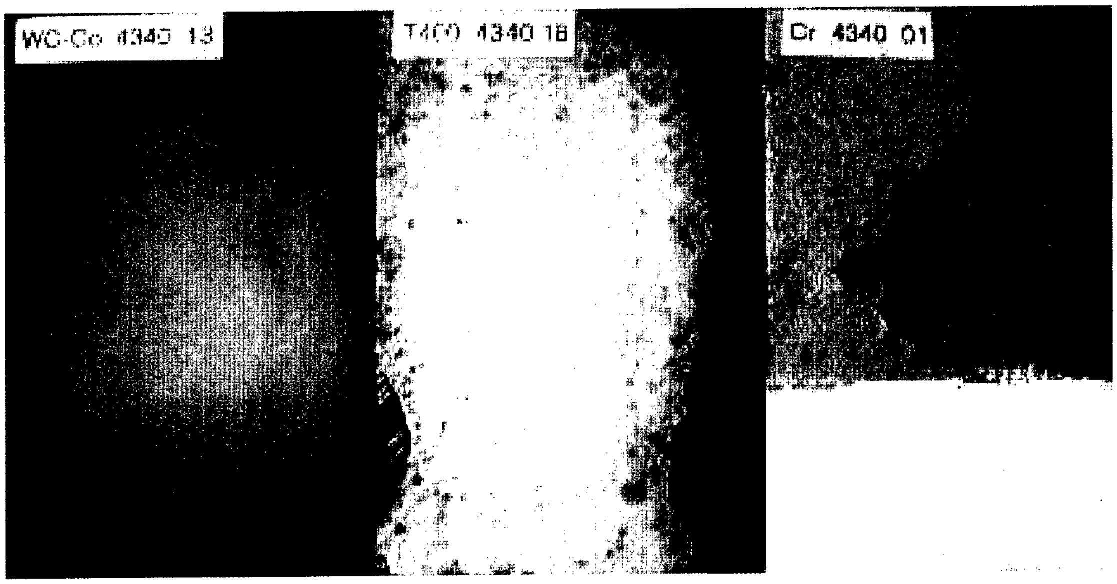


Figure 3-30. HVOF WC-Co, Tribaloy 400 (T400) and EHC (Cr) on 4340 Steel Following Three-year Atmospheric Exposure (Samples shown subsequent to cleaning)

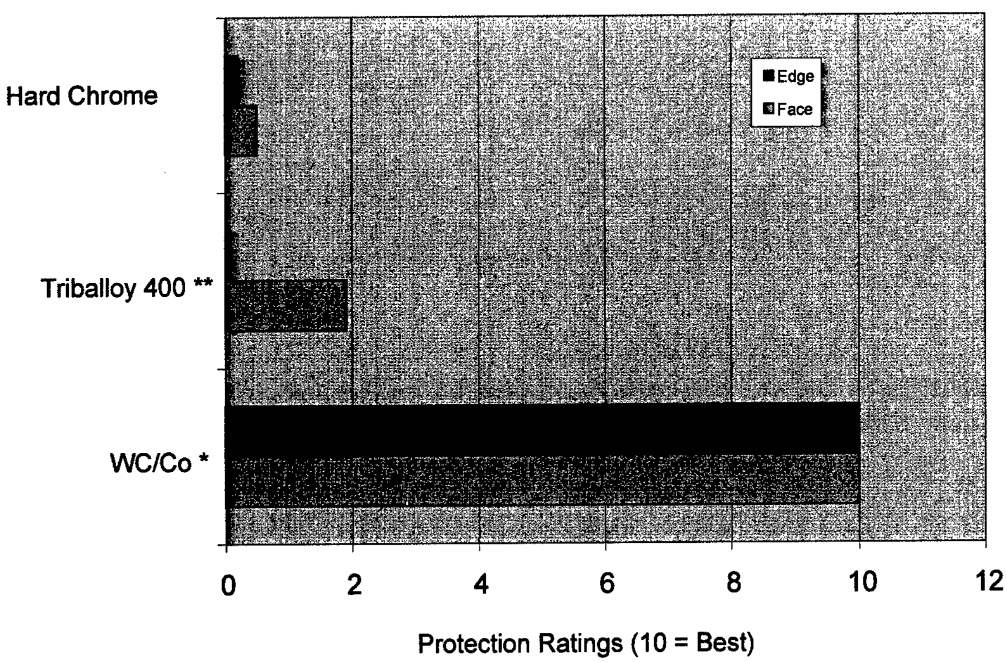


Figure 3-31. Protection Ratings for EHC, HVOF Tribaloy 400, and HVOF WC-17Co on 4340 Steel after Three-year Atmospheric Exposure

Table 3-28. Average Value of the Protection Rating for Samples that had Undergone a Three-year Atmospheric Exposure

Coating	Substrate	Protection - Face	Protection - Edge
T400	4340 steel	1.9	0
83WC/17Co	4340 steel	10.0	10.0
EHC	4340 steel	0.5	0.2

Table 3-27. Average Value of the Protection Rating for Samples that had Undergone 1,000 Hours of ASTM B117 Testing

Coating	Substrate	Protection - Face	Protection - Edge
T400	4340 steel	1.6	1.0
83WC/17Co	4340 steel	3.4	3.2
EHC	4340 steel	3.2	2.0

3.4.3. Rationale for JTP testing

With concurrence of the stakeholders the corrosion, a non-standard specimen shape was used in an attempt to better represent the typical rod-shaped components on which HVOF would most likely be employed. The specimen shape was a 1" diameter round rod 6" long, scribed when necessary. Both DoD standard ASTM B117 and GM 9540 cyclic tests were done to simulate service conditions. Because Boeing usually specifies a Ni sublayer beneath the EHC, and a sealant applied to the coating surface, while most depots deposit EHC directly on the substrate and do not apply a sealer, the test matrix incorporated combinations of these various conditions.

3.4.4. Landing gear original JTP testing

3.4.4.1. JTP specimen fabrication and deposition methodology

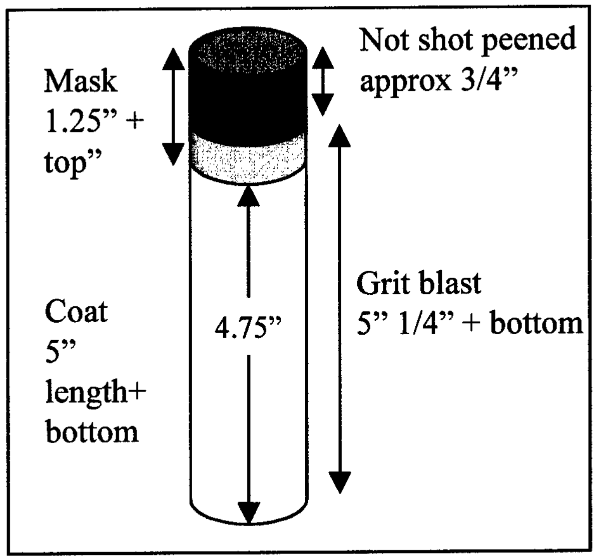


Figure 3-32. Corrosion Coupon, 1" Diameter Bar

A. Electrolytic hard chrome (EHC) was deposited in accordance with MIL-STD-1501, supported by QQ-C-320. The thicknesses was 0.003" and 0.010" +/- 0.0005" subsequent to grinding (i.e., coatings were deposited approximately 0.002" to 0.003" thicker than specified and then ground to final dimension). The coatings were applied to the curved surfaces of the rods over a length of 4.75" (see Figure 3-32). It was not necessary to apply the coatings to the ends. A sulfamate Ni underlayer was applied to a minimum thickness of 0.0015" in accordance with specification QQ-N-290 on some of the rods that received the EHC coating (see test matrix, Table 3-31). Subsequent to deposition, each EHC coating was ground to a surface finish of 16 microinches (+0/-4 microinches) using low-stress grinding techniques in accordance with specification MIL-STD-866. Subsequent to grinding, on some of the EHC coatings (see test matrix, Table 3-31), a polystyrene resin impregnation sealer was applied in accordance with P.S. 11501.

B. WC-17Co HVOF coatings were deposited in accordance with Boeing specification BAC 5851, Class 2, Type I, while WC-10Co4Cr HVOF coatings were deposited in accordance with Boeing specification BAC 5851, Class 2, Type XVII with the following additions or clarifications. The HVOF coatings were deposited using a Sulzer Metco Diamondjet hybrid gun with hydrogen as the fuel gas. The WC-Co powder material was Sulzer-Metco Diamalloy 2005 and the WC-CoCr powder material was Sulzer-Metco 5847. Uniform deposition conditions were utilized for all specimens. Air cooling was utilized to ensure the specimen surface temperature did not exceed 350^{o} F. The thicknesses was 0.003" and 0.010" (+/- 0.0005") subsequent to grinding (i.e., coatings were deposited approximately 0.002" to 0.003" thicker than specified and then ground to final dimension). All HVOF coatings were deposited to an Almen number of 3-12N. Subsequent to deposition, each coating was ground to a surface finish of 8 microinches (+0/-2 microinches) in accordance with specification BAC 5855 with the following modifications:

- ❑ Spec. paragraph 8.3.b.(1): If the excess coating thickness was less than 0.004", then rough grinding was not required. A minimum of 0.002"

stock removal (per side, or 0.004" on diameter) was required for finish grinding. The finishing in-feeds did not exceed a maximum of 0.0005" for 100 or 120 grit, 0.0004" for 150 grit, 0.0003"for 180 grit, 0.0002" for 220 grit, or 0.0001" for 320 or 400 grit.

- Spec. paragraph 8.3.b.(3): A finishing cross feed or traverse rate of 1/8 to 1/12 wheel width per workpiece revolution was used.
- Spec. paragraph 8.3.c.(4): Hardness – L, M, N, P or R
- Spec. paragraph 8.3.d: When grinding ID or OD surfaces, the work had a speed of 50 to 100 surface feet per minute.
- Subsequent to grinding, on some of the HVOF coatings a Metco URS sealer was applied (see test matrix, Table 3-31).

Subsequent to coating and grinding, an inert epoxy (Mil-P-24441 formula 150 and 152) was placed on the ends of the specimens to ensure no galvanic couple existed between the coated and uncoated sections. An arrow was scribed on the upper end of each specimen indicating the "up" direction during the corrosion tests. For those specimens with the scratches, the "up" position corresponded to the linear scratch being uppermost during the corrosion test.

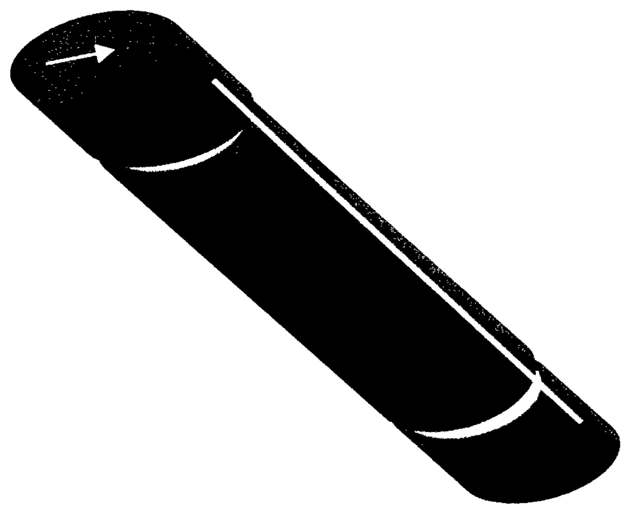


Figure 3-33. Illustration of Scratched Corrosion Test Specimen

One specimen in each group of five had multiple scratches made in the coating. These scratches were made using a diamond indenter (such as a Rockwell C indenter) and the scratches were such that they penetrated through the coating into the substrate. Two scratches were made around the circumference of the specimen 3-inches apart and a linear scratch was made 3.5" inches in length, crossing both circumferential scratches as shown in Figure 3-33.

3.4.4.2. JTP test methodology

Specification:	ASTM B117, "Standard Practice for Salt Spray (fog) Apparatus, Operating"; GM 9540 P/B, "GM Corrosion Test"
Modifications:	Round bar specimens in place of standard flat plate.
Significance:	Landing gear are subject to corrosion environments. (Note, however, that because of its microcracked surface, EHC is not generally used by itself for corrosion resistance.)
Sample types:	1" dia rods, 6" long, Circumference ground to a surface finish of 32-64 microinches prior to coating.

Sample materials: 4340, 300M, Aermet 100. 1"-diameter round bar. All bar stock for each material came from the same lot.

Sample heat treat: Vacuum heat treated specimens to the same tensile strength as for fatigue specimens (260-280 ksi for 4340; 280-300 ksi for 300M; 280-290 ksi for A100).

Pre-coating prep: **Shot Peen:** The circumference was shot peened in accordance with AMS-2432 under computer control using wrought steel, S230, Almen 8-10A. All curved surfaces were shot peened to 100% coverage, with the exception of a 0.75"-inch length at the end of each rod.

Grit blast prior to coating: For the EHC-coated specimens, a 5" length was grit blasted with 180-220 grit aluminum oxide or glass beads in accordance with standard procedure for hard chrome plating (see Figure 3-32). For HVOF coated specimens a 5" length was grit blasted with 54 grit aluminum oxide at 60 psi at 90° angle of impingement in accordance with MIL-STD-1504.

Coatings: EHC, WC-Co, WC-CoCr, ground

Coating thicknesses: 0.003" and 0.010"

Test equipment: Q-Fog Model CCT600 or equivalent salt spray chamber at ambient temperature. Specimen holders (made from an inert material such as teflon) were made to place the rods with at least 4" of the specimen extending out from the holder, at 45 degrees to the vertical. The scribed arrows on the ends always pointed vertically to keep the scribe uppermost.

3.4.4.2.1. Test Description

Three types of corrosion tests were conducted.

1. **Salt Fog Corrosion Test.** This test was conducted in accordance with ASTM B117-94. In this test, the samples were exposed to a salt fog made from a 5% NaCl solution maintained within a pH range of 6.5 and 7.2. The temperature in the salt fog chamber was held at 35°C. The specimens were visually inspected for surface corrosion after 125 hours, and every 125 hours thereafter. The samples were removed at 500 and 1,000 hours for photographing.

2. **GM Cyclic Corrosion Test.** This test was conducted in accordance with GM9540P/B protocol, which is indicated in Table 3-29. At each 500 hour interval, the specimens were removed from the test chamber, inspected, and photographed.

3. **SO_2 Salt Fog Test.** This test was conducted in accordance with ASTM G85-85. The samples were visually inspected at 48 hours, 96 hours, and every 100 hours between 200 and 1,000 hours. After 500 and 1,000 hours exposure the specimens were removed and photographed.

Table 3-29. GM 9540 Test Protocol

Solution:	0.9% NaCl, 0.1% $CaCl_2$ and 0.25% $NaHCO_3$		
pH:	6.0 – 8.0		
Test protocol:	**Atmosphere**	**Temp.**	**Time**
Step 1	Sub-cycle step 2-3 repeat 4 times		
Step 2	Salt mist	25C	15 min
Step 3	Dry-off	25C	75 min
Step 4	Dry-off	25C	120 min
Step 5	RH 95-100%	49C	8 hours
Step 6	Dry-off	60C	7 hours
Step 7	Dry-off	25C	1 hour
Step 8	Final step, go to step 1		
Note: RH = relative humidity			
Test duration:	2000 hrs		
Examined every	125 hrs		

Table 3-30. Table of Protection Rankings/Ratings

Defect area (%)	Rank #
0	10
>0 – 0.1	9
>0.1 – 0.25	8
>0.25 - 0.5	7
>0.5 – 1	6
>1 - 2.5	5
>2.5 – 5	4
>5 – 10	3
>10 – 25	2
>25 – 50	1
>50	0

Based on visual inspection, a ranking was applied to each specimen at each interval of inspection and these rankings were tabulated and displayed graphically. The rankings were assigned in accordance with ASTM B537-70 as in Table 3-30. In general, when the ranking of a specimen reached a value of 1, it was considered to have failed the corrosion test and was removed from the test cabinet.

The corrosion test matrix is given in Table 3-31.

Table 3-31. Corrosion Test Matrix

Test	Material	Coating	Thickness	Ni sublayer	Sealed	# specimens
B117	4340	Uncoated	N/A	N/A	N/A	5
B117	4340	EHC	3	No	No	5
B117	4340	EHC	3	Yes	No	5
B117	4340	EHC	3	No	Yes	5
B117	4340	EHC	10	No	No	5
B117	4340	EHC	10	No	Yes	5
B117	4340	EHC	10	Yes	No	5
B117	4340	WC/Co	3	no	No	5
B117	4340	WC/Co	3	no	Yes	5
B117	4340	WC/Co	10	no	No	5
B117	4340	WC/Co	10	no	Yes	5
B117	4340	WC/Co-Cr	3	no	No	5
B117	4340	WC/Co-Cr	10	no	No	5
B117	300M	EHC	3	no	No	5
B117	300M	EHC	3	no	Yes	5
B117	300M	EHC	3	yes	No	5
B117	300M	EHC	10	no	no	5
B117	300M	WC/Co	3	no	no	5
B117	300M	WC/Co	3	no	yes	5
B117	300M	WC/Co	10	no	no	5
B117	Aermet 100	EHC	3	no	no	5
B117	Aermet 100	EHC	3	no	yes	5
B117	Aermet 100	EHC	3	yes	no	5
B117	Aermet 100	EHC	10	no	no	5
B117	Aermet 100	WC/Co	3	no	no	5
B117	Aermet 100	WC/Co	3	no	yes	5
B117	Aermet 100	WC/Co	10	no	no	5

Table 3-31. Corrosion Test Matrix (continued)

Test	Material	Coating	Thickness	Ni Sublayer	Sealed	# specimens
GM	300M	EHC	3	no	no	5
GM	300M	EHC	3	no	yes	5
GM	300M	WC/Co	3	no	no	5
GM	300M	WC/Co	3	no	yes	5
GM	Aermet 100	EHC	3	no	no	5
GM	Aermet 100	EHC	3	no	yes	5
GM	Aermet 100	WC/Co	3	no	no	5
GM	Aermet 100	WC/Co	3	no	yes	5
SO_2	4340	Uncoated	N/A	N/A	N/A	5
SO_2	4340	EHC	3	no	no	5
SO_2	4340	EHC	3	no	yes	5
SO_2	4340	EHC	3	yes	no	5
SO_2	4340	EHC	10	no	no	5
SO_2	4340	WC/Co	3	no	no	5
SO_2	4340	WC/Co	3	no	yes	5
SO_2	4340	WC/Co	10	no	no	5
SO_2	4340	WC/Co-Cr	3	no	no	5
SO_2	4340	WC/Co-Cr	10	no	no	5
SO_2	300M	EHC	3	no	no	5
SO_2	300M	EHC	3	no	yes	5
SO_2	300M	EHC	3	yes	no	5
SO_2	300M	WC/Co	3	no	no	5
SO_2	300M	WC/Co	3	no	yes	5
SO_2	Aermet 100	EHC	3	no	no	5
SO_2	Aermet 100	EHC	3	no	yes	5
SO_2	Aermet 100	EHC	3	yes	no	5
SO_2	Aermet 100	WC/Co	3	no	no	5
SO_2	Aermet 100	WC/Co	3	no	yes	5
					Total	275

3.4.4.3.Test results

As of the date of writing this report, the SO_2 corrosion testing had been completed but analysis of the samples was still in progress. Therefore, the results presented herein will be only for the B117 salt fog and GM9540 cyclic corrosion testing.

Appearance ratings for the samples were determined at 125 hour intervals during the B117 test. After exposure to the accelerated tests, all specimens were removed from the salt fog cabinet and were cleaned with a Scotch 3M abrasive pad to remove loosely adherent corrosion products then dried with cotton cloth. The corrosion product was removed using the abrasive pad because in many instances it was so voluminous that it masked the surface. After cleaning, it was possible to identify surface defects such as blisters or pits (see Figure 3-34 as an example). Removing the blisters and portions of the coating that were undercut by corrosion provided a better representation of the area that was affected by corrosion. A protection rating for the coating, i.e. how well it protected the substrate, was then determined. The appearance ratings are not reported here as they are not as good a metric for the degree of corrosion as the protection rating. The ability of the coating to protect the substrate and the corrosion of the coating were considered when assigning a protection rating for the HVOF coatings. Protection ratings for the EHC coatings only considered defects in the coating as the coating did not show any visual signs of corrosion. The four replicate samples were examined and given a protection rating (0-10) in accordance with ASTM B 537 as indicated above. The arithmetic average of these four samples was computed and used for all data analysis. The scribed samples were handled differently; the maximum creep in millimeters from the center of the scribe line was recorded for the vertical and separately for the horizontal scribes. This information was tabulated and used in the subsequent data analysis. The scribe creepage between the horizontal and vertical scribes were seen to be comparable in all but two sample groups and only the vertical scribe creep was used for the comparison of the various coatings' performance (with the exceptions noted). In several specimens, corrosion had severely damaged the sample and it was uncertain whether any of the applied coating was intact near the scribe. To confirm the nature of the corrosion damage, both optical and scanning electron microscopy were performed on these samples.

The examination of the samples following the 1,000-hour exposure clearly showed that the base alloy influenced the corrosion behavior. As a result, the discussion of the results is divided into sections according to the base alloy. Appendix 3 of the JTR [3.1] contains the individual protection ratings and scribe creep values for all samples.

3.4.4.3.1. 4340 Steel in ASTM B-117

The experimental results for these samples are presented on the following pages in both bar chart (Figure 3-35) and radar plot form (Figure 3-36). In general, the EHC coating outperformed the WC-Co coating in every direct comparison. Figure 3-38 shows the 4340 steel with the various 0.010" hard chrome coatings. The overall best performance for a coating to protect this base metal was the EHC with a nickel sublayer. This combination achieved the highest protection ratings of any coating. The use of an

organic sealer generally enhanced the performance of a given coating system but the overall performance levels of any coating combination with sealer did not match the performance of EHC with the nickel sublayer. Some modest enhancement in corrosion performance was seen by increasing the coating thickness; 0.010”-thick coatings generally performed better than the same coating composition at 0.003” in thickness.

The 0.003”-thick WC-Co coatings without sealer performed poorly, receiving a rating of 1. The coating was cracked and severely undercut. The 0.010”-thick coating without sealer received a rating of 2. In this case, there were no cracks in the coating or any signs that the coating had been breached. However, corrosion of the coating had occurred. The samples had a mottled appearance with portions of the coating corroding but the rest of the coating not affected. Under a light microscope, the attack in the corroded regions appeared to be a generalized dissolution. This type of attack on the coatings was also seen with the other unsealed HVOF coating/substrate combinations. A possible opportunity for improvement of the WC-Co was seen by the addition of chromium to the composition (see Figure 3-35, Figure 3-36, and Figure 3-37). The 0.003”-thick WC-CoCr had portions of the coating that were removed and some undercutting. Corrosion of the coating also occurred and the average protection rating was 3.75. The 0.010”-thick WC-CoCr without sealer had a protection rating of 7.75. In this series, three of the samples showed cracking of the coating in isolated areas and some undercutting of the coating in these areas. In two of the latter cases, the epoxy mask at the top of the rod appeared to be compromised and this was the site that appeared to be the origin of the undercutting and cracking. The corrosion of the 0.010”-thick WC-CoCr coatings was light. The B117 results clearly demonstrate the performance enhancement of the chromium-containing alloy without relying on an organic sealer or on a Ni underlay. Protection ratings of the WC-CoCr coating equaled or exceeded those of EHC with no sealer or Ni sublayer. Figure 3-39 shows the 0.010”-thick EHC coatings and the 0.010”-thick WC-CoCr coating. While the 0.010”-thick EHC with the nickel sublayer was the best overall performer with a rating of 9.7, the 0.010”-thick WC-CoCr test specimens certainly showed this modification to be promising, receiving an average rating of 7.75 – as good as EHC without the Ni underlayer.

The 0.003”-thick WC-Co with the organic sealer coating provided a protection rating which equaled the general performance of the EHC without nickel. This result needs confirmation however because the 0.010”-thick WC-Co coating with organic sealer showed poor performance. Certainly this is counterintuitive; a 0.010”-thick coating of the equivalent composition ought to outperform a 0.003”-thick coating in the same corrosion test. The explanation most likely lies in the mechanical integrity of the sealer. Both organic sealers evidenced some blistering, which was much more severe in the sample with the 0.010”-thick coating. The damage to the organic coating appeared much worse for the 0.010”-thick coating, which allowed the salt solution to penetrate and undercut this sealer. Once the adhesion between the sealer and the metal clad is compromised, corrosion can take place leading to similar results for this tungsten carbide coating as with the unsealed versions. Figure 3-40 shows the corrosion that has occurred beneath a removed blister. The coating adjacent to the blister is easily peeled away from the substrate indicating poor adhesion.

The samples with the 0.003”- and 0.010”-thick WC-Co coatings and sealer had a scribe

creepage of 12 mm. Without sealer, scribe creepage was 19 mm for the 0.003"-thick coating and 15 mm for the 0.010"-thick coating.

The scribe creepage results for the WC-CoCr coating were distinct from other results. Both scribed samples showed large scribe creepage from the horizontal scribes, running practically the entire length of the sample. The vertical scribe creepage values were 11 mm and 18 mm while the maximum creepage from the horizontal scribe was 58 mm and 47 mm respectively. Severe undercutting of the metal coating was observed and disbonding of the coating was evident in both samples. Corrosion products had separated the metal coating from the base metal. This occurred at only one location on each sample but only at a horizontal scribe line. At present, there is no explanation for this result but it seems anomalous in light of the performance of the other WC-Co samples.

Five uncoated 4340 rods were placed in the B117 test chamber as controls. These rods experienced severe corrosion and were removed at 250 hours of exposure. The rating for each of these samples was 0.

3.4.4.3.2. 300M Steel in B 117

Figure 3-41 and Figure 3-42 present the experimental results in bar chart and radar plot formats for the base metal 300M with the EHC and WC-Co coatings after the salt fog test. The same general trends observed with the 4340 steel results in salt fog testing were seen for this substrate as well. Overall, there were fewer coating variations tested on this substrate but the results for those specimens are clear. The general performance of the EHC coating exceeds that of the WC-Co. All EHC coatings achieved protection ratings of 8 or above, with the EHC with a nickel sublayer achieving an almost perfect protection rating. By contrast, the 0.003"-thick WC-Co coating without sealer showed a 0 protection rating. These samples had severe undercutting and the substrate was heavily corroded. Simply increasing the coating thickness to 0.010" did improve the performance but the rating, 3.25, was still low. Two of the samples in the latter group had cracks in the coating and undercutting occurred. In these latter areas the coating was easily removed. The other two of the samples in this group had coatings that were intact. All of the unsealed WC-Co coatings showed a degree of corrosion and the corrosion product was removed from the samples during the cleaning process.

The use of an organic sealer with the WC-Co coating did show significant improvement in the protection rating. The 0.003"-thick coatings which had such poor performance without the sealer, improved to an average protection rating of 8 with sealer application. These results should be viewed with some caution however. The organic sealer layer was generally intact when the specimens were cleaned but blistering was noted on all these samples. The blisters were easily removed. In order to check the adhesion of the organic sealer to the underlying tungsten carbide, a water soak tape adhesion test was performed. Using 3M brand tape over a 2 cm x 2 cm area, 50% or more of the sealer was removed by tape pull normal to the surface, evidencing adhesion problems between the sealer and underlying WC-Co. If additional accelerated corrosion testing were performed, it is suspected that this organic layer would have failed leading to results similar to those above. There is no doubt the presence of an intact sealer layer acts as a barrier but adhesion issues should be addressed to ensure this barrier remains effective if WC-Co coatings are to be used with this substrate.

The scribe creep for the 0.003"-thick EHC coatings was between 5 and 9 mm whereas it was 10mm for the 0.003"-thick unsealed WC-Co coating. The scribe creep was 4 mm for WC-Co coating with sealer and 3 mm for the 0.010"-thick WC-Co coating.

3.4.4.3.3. 300M Steel in GM 9540 P

The experimental results are tabulated in Table 3-32 for these samples. All coating thicknesses were 0.003".

Table 3-32. GM Accelerated Corrosion Test Results for 300M Steel (Coating thickness 0.003")

Coating	Sealer applied	Protection rating	Vertical scribe creep, max (mm)
Cr	No	10	1.5
Cr	Yes	10	2.0
WC-Co	No	8.5	2.0
WC-Co	Yes	8	1.0

The accelerated cyclic corrosion test results indicate the EHC coatings have enhanced corrosion protection performance over the WC-Co coatings, although the WC-Co coatings did perform well in this test. On average the WC-Co coatings merited an 8 protection rating but the EHC coatings showed a rating of 10. Figure 3-43 is a photo of representative samples from each group. All of the unsealed WC-Co coatings were intact, i.e. no cracks or defects exposing the substrate were noted. However, all of the unsealed WC-Co samples showed a degree of corrosion and a light corrosion product was removed from the samples during the cleaning process. Vertical scribe creep results did not differentiate one coating from another, with all samples having a maximum creep of 2 mm or less.

3.4.4.3.4. Aermet 100 Steel in B 117

Figure 3-44 and Figure 3-45 present bar and radar charts that summarize the results for this base metal test series. The corrosion testing showed this base metal to be the best of the three for corrosion performance. Within the results from salt fog testing for just this base metal, EHC was again seen as superior. Consistent results with the previous base metal results were seen in that thicker coatings protect more than thinner coatings of the same chemical composition. A nickel metal underlayer with EHC offers superb resistance to corrosion with all other test samples performing worse. The 0.003"-thick WC-Co coatings performed poorly compared to EHC. All of the unsealed WC-Co coatings showed a degree of general corrosion and the corrosion product was removed from the samples during the cleaning process. The application of an organic sealer to the WC-Co did enhance its protection rating, as seen in the previous corrosion results.

Two of the samples with 0.003"-thick WC-Co HVOF coatings without sealer on Aermet 100 had one region where the coating had a crack. The cracked region was easily

removed and showed that some undercutting had occurred. The coating was not compromised in the other two samples in this group. All of the unsealed WC-Co coatings showed a degree of corrosion and the corrosion product was removed from the samples during the cleaning process. The 0.010"-thick WC-Co coatings showed no signs of cracks or defects that exposed the substrate. However, all of coatings showed a degree of corrosion and the corrosion product was removed from the samples during the cleaning process. The corrosion performance of the WC-Co coatings on A100 without sealer was better than on the other substrates with the same coating (see, for example, Figure 3-46 which is a photo of representative samples of the 0.003"-thick WC-Co HVOF coatings without sealer on 4340 steel, 300M, and Aermet 100 after the B117 test).

The superior performance of the coatings on Aermet 100 over the other substrate/coating combinations was evidenced by the scribe creepage results. Overall, there was almost no scribe creepage for the Aermet 100/coating combinations. The only significant deviation was the WC-Co coating with the sealer. Even though the overall appearance of the sealer-coated WC-Co was better, the scribe creepage increased to 3 mm maximum versus less than 1 mm for the other samples in this series. This supports the theory that intact organic sealers act as a barrier, but once damaged, they may enhance the corrosion at localized points. As with the 300M metal samples, once the organic sealer is damaged, adhesion between sealer and metal coating is compromised.

3.4.4.3.5. Aermet 100 Steel in GM 9540P

Results from this test set are reported in Table 3-33. All coatings were 0.003" thick.

Table 3-33. GM Accelerated Corrosion Test Results for Aermet 100 Steel (Coating thickness 0.003")

Coating	Sealer applied	Protection rating	Vertical scribe creep, max (mm)
Cr	No	10	0
Cr	Yes	10	0
WC-Co	No	8	0
WC-Co	Yes	9	0

Both sets of EHC specimens were rated at 10 while the WC-Co sets were rated at 8 and 9 for unsealed and sealed, respectively. All of the unsealed WC-Co coatings were intact, i.e. no cracks or defects exposing the substrate were noted. However, all of the unsealed WC-Co samples showed a degree of corrosion and a light corrosion product was removed from the samples during the cleaning process. Scribe creepage results were exceptional for this base metal. All test samples showed zero creep on both the horizontal and vertical scribes, the best results of the entire set of samples.

3.4.4.3.6. Comparison of performance of WC-Co and WC-CoCr coatings without sealer

Table 3-34 shows that the unsealed 0.010"-thick HVOF coatings were more effective in protecting the underlying substrate from corrosion compared to the 0.003"-thick HVOF

coatings. The unsealed coatings on the 4340 steel and Aermet 100 were completely intact, i.e, there were no cracks and/or defects exposing the substrate. However, the overall rating of these samples was lower because the coating had undergone corrosion. The WC-CoCr had the least amount of coating corrosion of the unsealed samples exposed to the B117 test protocol. Figure 3-47 shows samples with the various 0.010"-thick HVOF coatings on 4340, 300M and Aermet 100 that are intact.

Table 3-34. Percentage of Specimens with Intact Coatings and the Overall Protection Ratings for HVOF Coatings Without Sealer

Coating/substrate	0.003" coating		0.010" coating	
	% of specimens with intact coating	Overall rating	% of specimens with intact coating	Overall rating
WC-Co on 4340	0	1	100	2
WC-CoCr on 4340	0	3	25	7
WC-Co on 300M	0	0	50	2
WC-CoCr on A100	50	2	100	3

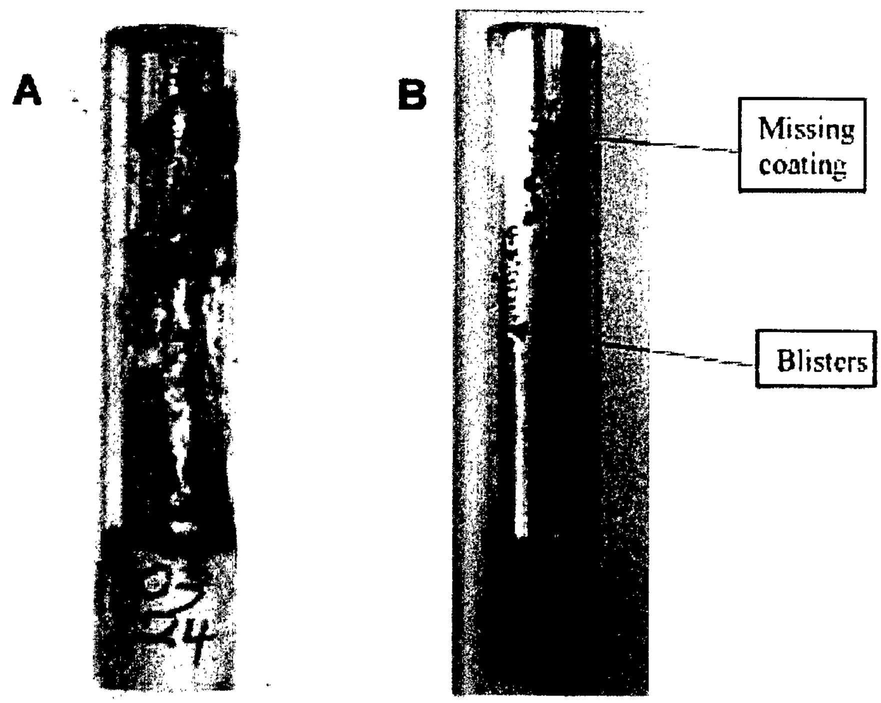


Figure 3-34. 0.003"-thick EHC Coating + Sealer on 4340 Steel After B117 Test: a) Before and b) After Cleaning

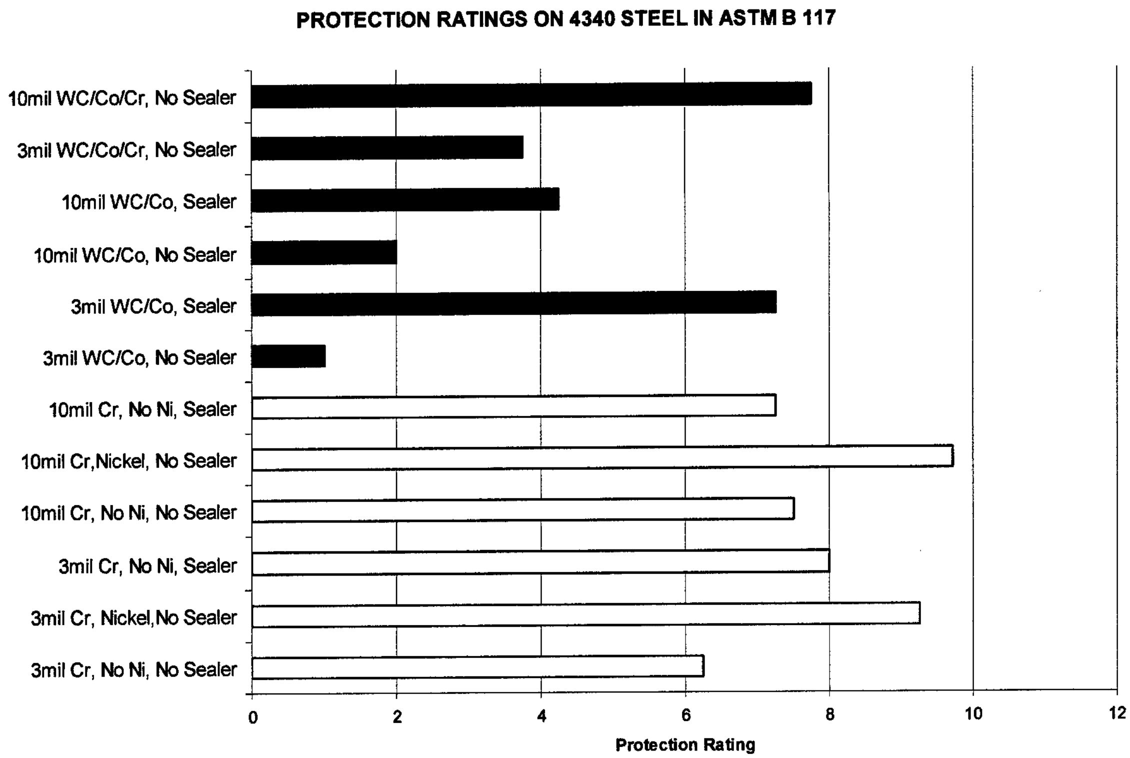


Figure 3-35. Protection Ratings on 4340 Steel After B117 Testing

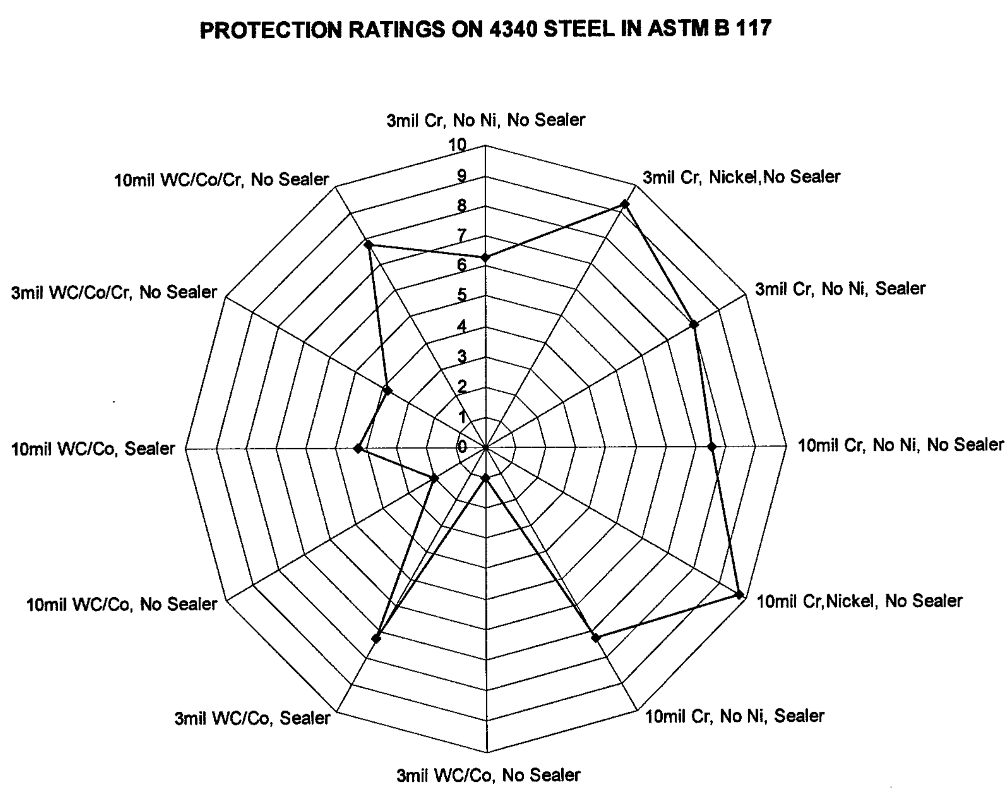


Figure 3-36. Radar Plot of the Protection Ratings on 4340 Steel After ASTM B117 Testing

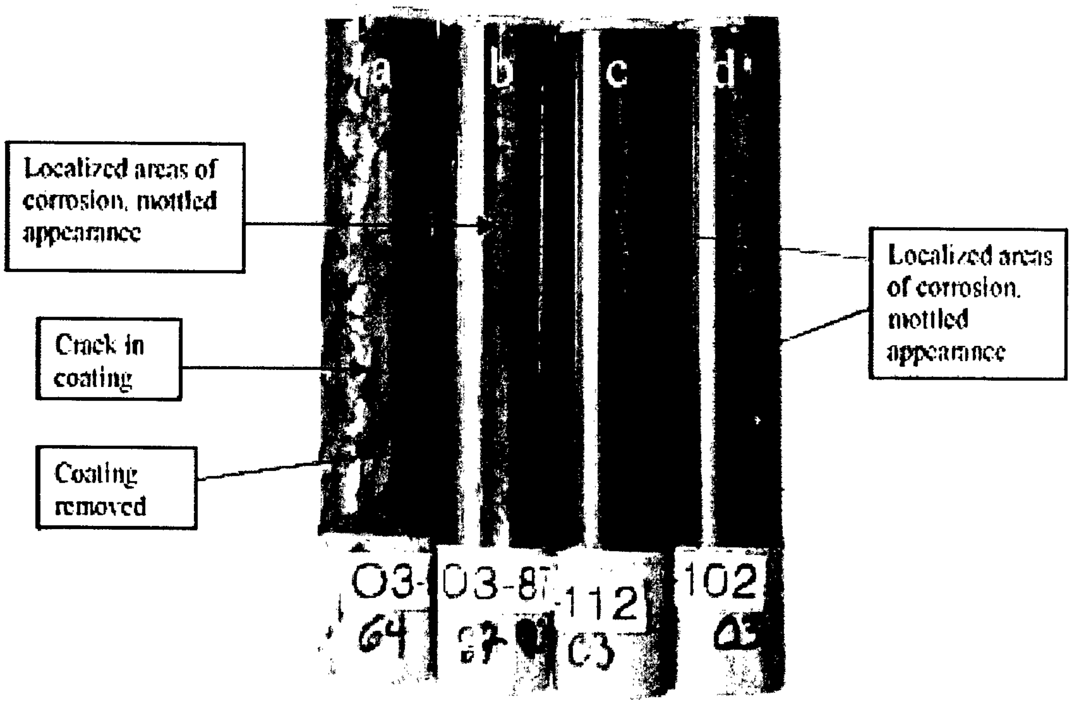


Figure 3-37. HVOF Coatings on 4340 Steel After the B117 Test: a) 0.003" WC-Co, b) 0.010" WC-Co, c) 0.010" WC-CoCr, and d) 0.003" WC-CoCr

Figure 3-38. 0.010"-thick EHC coatings on 4340 Steel with: a) Ni Sublayer, b) Sealer, and c) EHC Coating Only, After B117 Testing

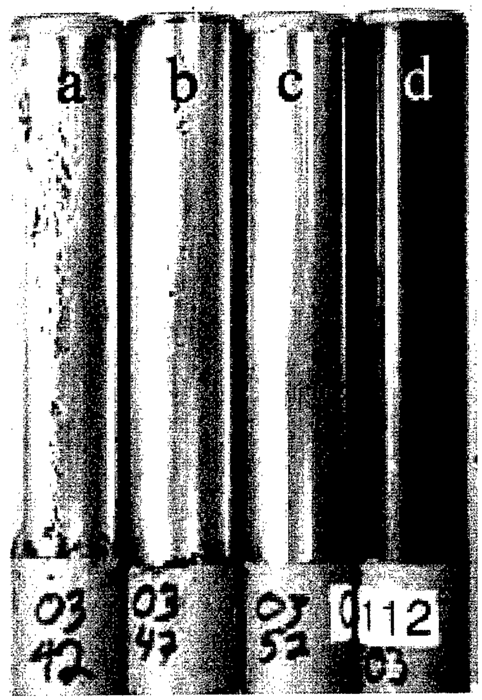


Figure 3-39. Coatings on 4340 Steel After the B117 Test: a) EHC Coating Only b) EHC with Sealer, c) EHC with Ni Sublayer, and d) 0.010"-thick WC-CoCr

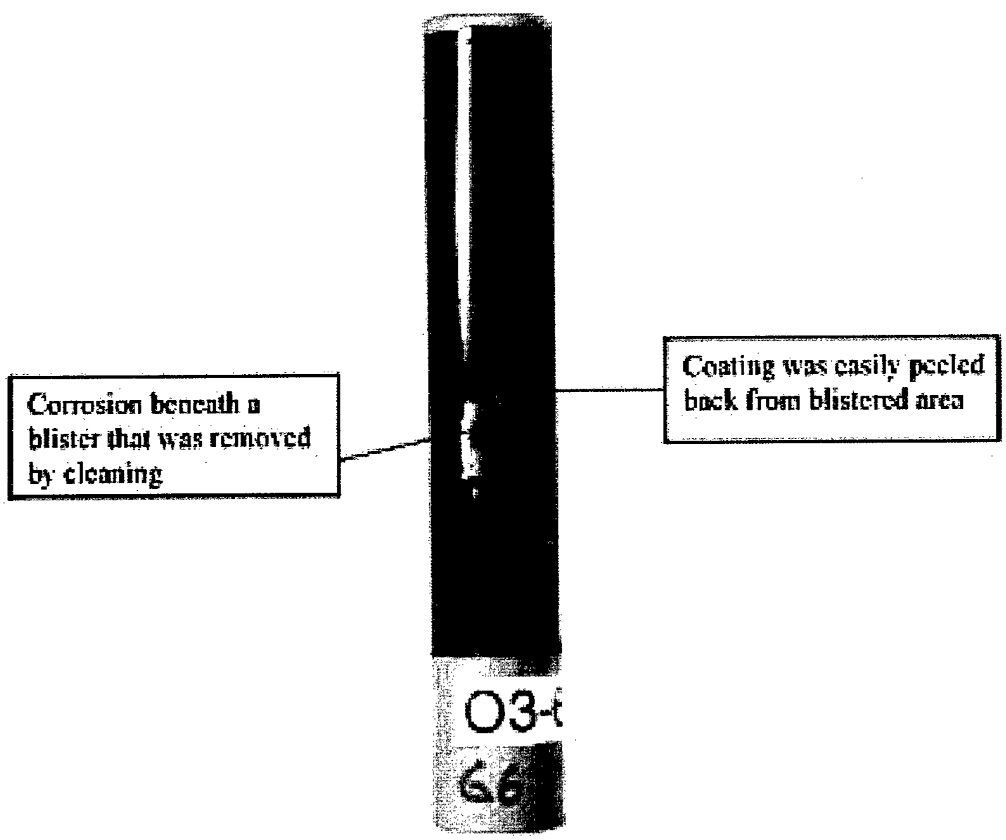


Figure 3-40. 0.003"-thick HVOF WC-Co Coating on 4340 Steel with Sealer After Blister has been Removed

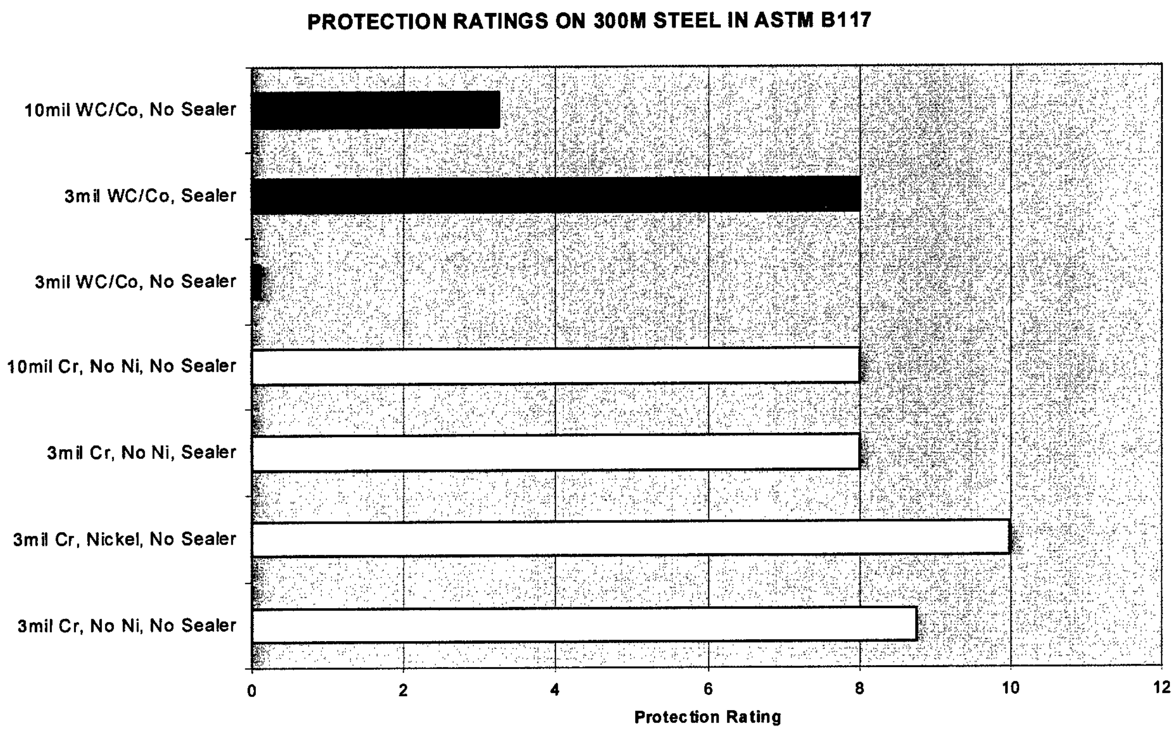


Figure 3-41. Protection Ratings on 300M After ASTM B117 Testing

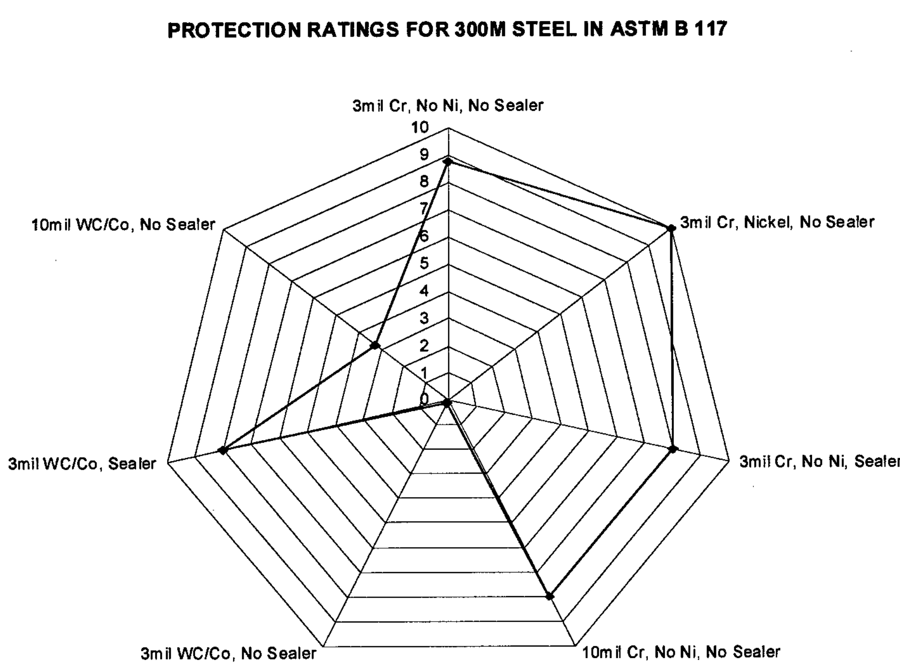


Figure 3-42. Radar Plot of the Protection Ratings on 300M After ASTM B117 Testing

Figure 3-43. 0.003"-thick Coatings on 300M After GM 9540P Testing: a) EHC Only, b)WC-Co, c) WC-Co With Sealer, and d) EHC With Sealer

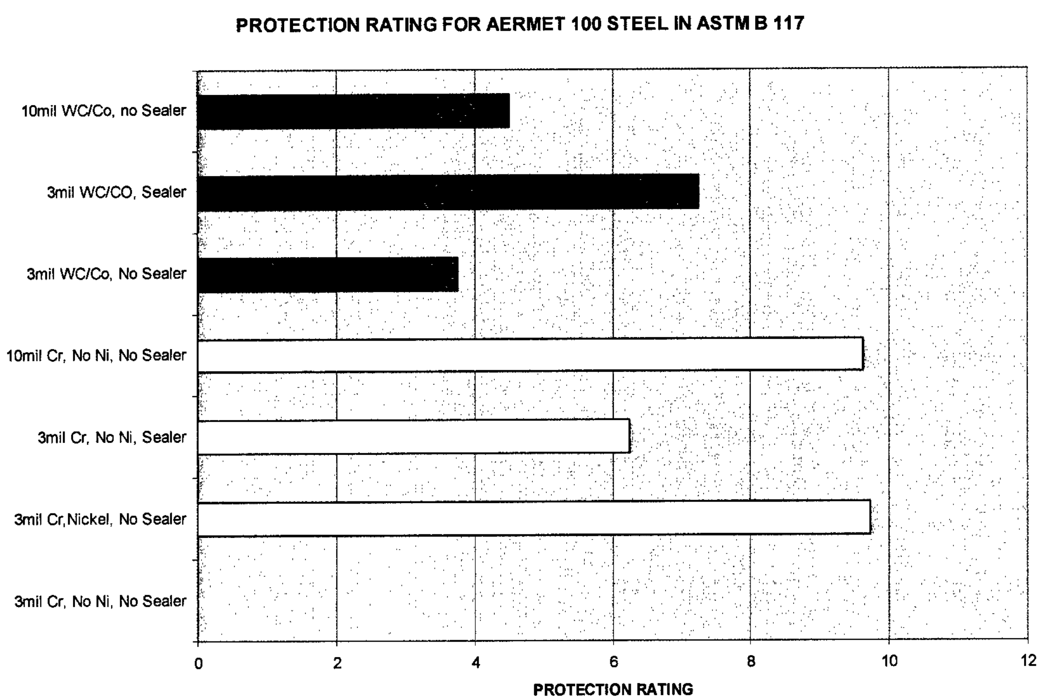


Figure 3-44. Protection Ratings on Aermet 100 After ASTM B117 Testing

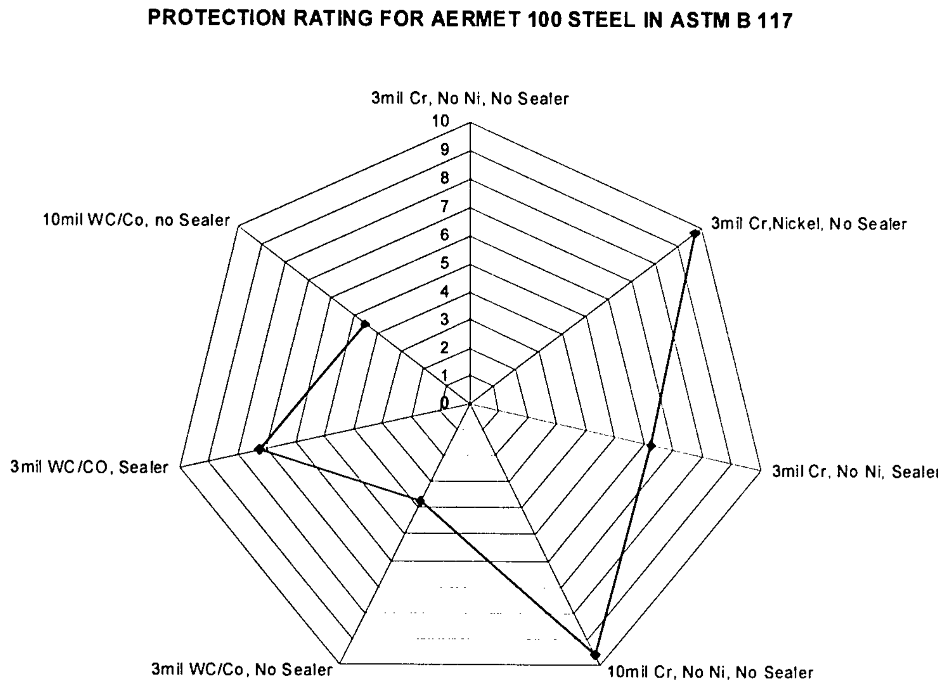


Figure 3-45. Radar Plot of the Protection Ratings on Aermet 100 After ASTM B177 Testing

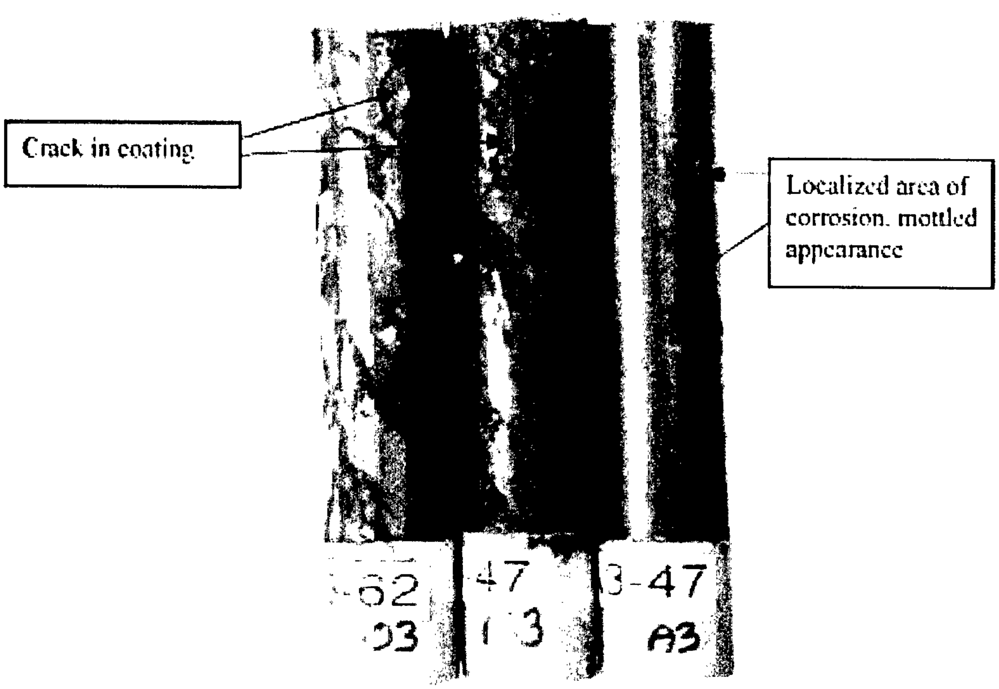


Figure 3-46. 0.003"-thick WC-Co HVOF coating on 4340 Steel, 300M, and Aermet 100 After the B117 Test

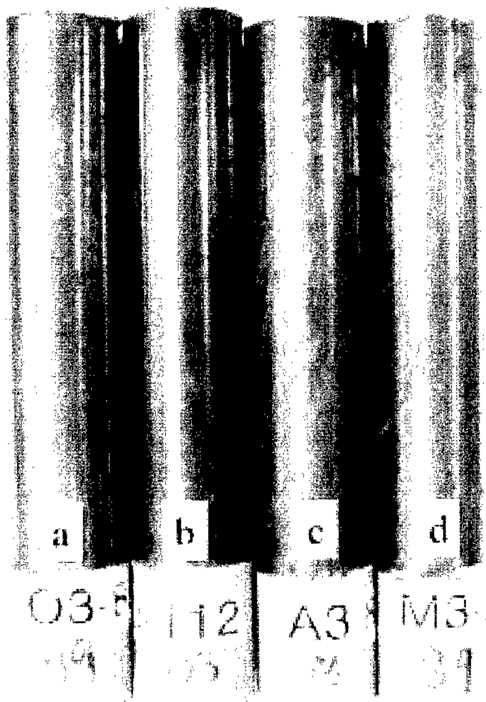


Figure 3-47. 0.010"-thick HVOF Coatings: a) WC-Co on 4340, b)WC-CoCr on 4340, c) WC-Co on 300M, and d) WC-Co on Aermet 100 After the B117 Test

3.4.5. Additional B117 Corrosion Testing

3.4.5.1.Background

It was apparent that there were significant differences between the results that had previously been obtained for B117 testing in which the HVOF WC-Co coatings performed comparably to the EHC and the results obtained for B117 testing conducted under the Landing Gear JTP where the performance of the WC-Co coatings was inferior to the EHC. In addition, there were the results for the atmospheric corrosion testing discussed in Section 3.4.2 in which the WC-Co coatings performed substantially better than the EHC coatings after exposure for three years.

In order to attempt to determine the reason for the relatively poor performance of the WC-Co coatings in the Landing Gear JTP tests, additional corrosion testing was conducted. It should first be pointed out that the B117 protocol calls for only flat samples to be tested; our use of one-inch-diameter rods was a deviation from the protocol. Another difference between the earlier B117 and atmospheric tests and those conducted for the Landing Gear JTP was that the former coatings were tested as-sprayed and the latter were ground to a surface finish Ra of 8 microinches. Finally, it was observed on many of the rod samples tested under the Landing Gear JTP that the epoxy sealer that was used to seal the uncoated ends had been breached, which allowed the corrosive media to attack the base material, leading to corrosion proceeding underneath the WC-Co and subsequent fracturing and spallation of the coatings.

3.4.5.2. Specimen Preparation and Coating Deposition

To attempt to address these issues, additional corrosion testing was performed. This involved specimens that consisted of one-inch-diameter 4340 and 300M rods, and 3" by 4" 4340 plates. To ensure there were no differences between WC-Co coatings deposited at different facilities using supposedly the same parameters, two different vendors were used, Hitemco and Southwest Aeroservice. Southwest Aeroservice also deposited the EHC coatings.

The sample preparation (e.g., shot peening, grit blasting) and coating deposition parameters were identical to those used for the Landing Gear JTP samples. For the six-inch-long rods, the area on each sample that was coated was slightly different than for the JTP samples. As before, the flat ends were not coated. On the curved surface, at one end of the rod, the coating terminated one-inch from the end. At the other end, the coating terminated one-quarter-inch from the end. Thus, the actual length of the coated surface was 4-3/4". On the plates, only one face was coated. On that face, the three-inch-wide dimension was coated edge-to-edge and on the four-inch-wide dimension the coating terminated one-half-inch from each edge. Thus, the actual area that was coated was three by three inches. Application of the coatings followed Boeing specification sheet 160T1000 which required that the HVOF coatings not terminate with a square edge, but that they were tapered from full to zero thickness over a minimum length of 0.006". Following deposition, some of the coatings were ground the same as for the previous samples and some were tested as-deposited.

One major difference was the material used to seal the non-coated areas on the samples. Cadmium plating followed by a post chromate treatment per Mil-Spec QQ-P-416F was applied to the noncoated areas and the coating/substrate termination areas, with the cadmium/chromate overlapping approximately 0.1" onto the HVOF and EHC coatings.

Table 3-35 to Table 3-37 summarize all of the coatings that were deposited onto the 4340 and 300M rods and the 4340 plates. The testing required a total of 84 samples.

Table 3-35. Sample Matrix for Supplemental Corrosion Testing – 4340 Rods

Coating	Thickness	Ground	Spray Co.	# of samples
WC-Co	0.003"	Y	H	2
WC-Co	0.003"	Y	S	2
WC-Co	0.003"	N	H	2
WC-Co	0.003"	N	S	2
WC-Co	0.010"	Y	H	2
WC-Co	0.010"	Y	S	2
WC-CoCr	0.003"	Y	H	2
WC-CoCr	0.003"	Y	S	2
WC-CoCr	0.003"	N	H	2
WC-CoCr	0.003"	N	S	2
WC-CoCr	0.010"	Y	H	2
WC-CoCr	0.010"	Y	S	2
EHC	0.003"	Y	S	2
EHC	0.010"	Y	S	2
Notes:		Y = Yes	H = Hitemco	
		N = No	S = Southwest Aeroservice	

Table 3-36. Sample Matrix for Supplemental Corrosion Testing – 300M Rods

Coating	Thickness	Ground	Spray Co.	# of samples
WC-Co	0.003"	Y	H	2
WC-Co	0.003"	Y	S	2
WC-Co	0.003"	N	H	2
WC-Co	0.003"	N	S	2
WC-Co	0.010"	Y	H	2
WC-Co	0.010"	Y	S	2
WC-CoCr	0.003"	Y	H	2
WC-CoCr	0.003"	Y	S	2
WC-CoCr	0.003"	N	H	2
WC-CoCr	0.003"	N	S	2
WC-CoCr	0.010"	Y	H	2
WC-CoCr	0.010"	Y	S	2
EHC	0.003"	Y	S	2
EHC	0.010"	Y	S	2

Table 3-37. Sample Matrix for Supplemental Corrosion Testing – 4340 Plates

Coating	Thickness	Ground	Spray Co.	# of samples
WC-Co	0.003"	Y	H	2
WC-Co	0.003"	Y	S	2
WC-Co	0.003"	N	H	2
WC-Co	0.003"	N	S	2
WC-Co	0.010"	Y	H	2
WC-Co	0.010"	Y	S	2
WC-CoCr	0.003"	Y	H	2
WC-CoCr	0.003"	Y	S	2
WC-CoCr	0.003"	N	H	2
WC-CoCr	0.003"	N	S	2
WC-CoCr	0.010"	Y	H	2
WC-CoCr	0.010"	Y	S	2
EHC	0.003"	Y	S	2
EHC	0.010"	Y	S	2

As can be seen from Table 3-35 to Table 3-37, there were two samples for each condition. One complete set of samples was inserted into the Q-Fog model corrosion test cabinet at the Naval Research Laboratory Key West (NRLKW) and the other complete set was inserted into the Q-Fog model corrosion test cabinet at the Kennedy Space Center (KSC). The samples were exposed for 1000 hours under the exact same conditions as for the previous Landing Gear JTP samples.

After the salt fog tests were complete, the samples were cleaned at NRL using water and Scotch Brite abrasive pads to remove loosely adherent corrosion products, then dried with laboratory cotton wipes. The corrosion products were removed using the abrasive pads to allow a better view of the coating surface, which was often obscured by the large volume of corrosion product and salt residue on the samples. After cleaning, it was possible to identify surface defects such as blisters or pits that could be more closely examined to determine if the coating was undercut and the base metal exposed. All examinations were conducted under a 10X stereomicroscope and protection and appearance ratings assigned per ASTM Standard B537.

3.4.5.3.Results and Discussion

In the following discussion, those samples previously tested under the Landing Gear JTP will be referred to as the "LGJTP" samples and those samples tested under this supplemental corrosion study will be referred to as the "Supplemental" samples. A general observation regarding the previous and current results was that the extent of corrosion was less for the Supplemental than for the LGJTP samples. Overall, fewer surface coating breaches were observed.

Figure 3-48 compares the 0.003"-thick WC-Co coatings on 300M steel from each data set.

Figure 3-49 is the same coating comparison on 4340 steel. The degree of cracking of the tungsten carbide coating in the LGJTP sample set is obvious relative to the Supplemental set. Even the EHC coating samples from the LGJTP set had some pitting damage but all EHC samples from the Supplemental set were judged to demonstrate excellent performance after the 1,000 hours salt fog exposure. Figure 3-50 shows the results from the LGJTP 0.003"-thick EHC coating versus the Supplemental equivalent sample. The pitting and coating breach in the upper right of the LGJTP sample set is evident.

The analysis of the LGJTP samples consisted of only recording a protection rating for each sample following cleaning to remove loose corrosion products. For these Supplemental samples, the recording of both an appearance and a protection rating provided a better understanding of the test results. The protection rating details how well the coating protected the base metal from corrosive attack by the salt fog. Protection ratings of 10 show the underlying metal was completely protected from corrosion while ratings of 4 and below show significant corrosion of the base metal. However, the appearance rating gives a relative scale to the level of corrosive attack on the coating itself. A specimen might have a protection rating of 10 but an appearance rating of 2, which indicates a substantial surface attack of the coating material. This may be of importance in that a coating's ability to resist corrosion does impact its service life. Coatings which undergo significant surface corrosion in salt fog are more likely to allow substrate corrosion in time compared to those coatings more impervious to attack. Appendix 3 in the JTR [3.1] provides the protection and appearance ratings for all of the tested samples.

3.4.5.3.1. Protection Ratings

As mentioned previously, the corrosion levels observed on the Supplemental samples were not as severe as those on the LGJTP samples. One likely explanation is that Cd was used to protect the top and bottom of each sample. The LGJTP samples used an epoxy resin formulation to protect the top and bottom of the samples although, as noted in the previous section, there were instances where the epoxy was breached allowing for undercutting of the coatings. Cadmium is the least noble (most active) of any of the metals used in the coatings or substrate materials. Further, the Cd was in direct contact with both the coating and the underlying substrate metal while the samples were in a condensing, electrolytic salt atmosphere. It is believed that the Cd metal served to protect the coating and substrate by acting as a sacrificial anode, i.e. providing cathodic protection, which led to the improved corrosion performance in the ASTM B117 test.

During the rating of the samples, the comment section in JTR Appendix 3 notes the condition of the Cd coating on the top (T) and bottom (B or BOT) of each specimen.

All flat panel specimens demonstrated good protection ratings and similar surface corrosion properties to the identical coatings in the rod geometry specimens (see Figure 3-54). As such, the flat panels added little clarity to this study and the remaining analysis will concentrate on the rod geometry samples.

For the 4340 metal rods, two of the NRL exposed samples had breached coatings as well as three of the KSC exposed samples. Those samples with failed coatings are indicated in Table 3-38, while the full data are shown in Figure 3-57.

Table 3-38. Failed Coatings on 4340 Substrates

NRLKW Exposed Samples	KSC Exposed Samples
WC-Co 0.003" Ground Hitemco	WC-Co 0.003" Ground Hitemco
WC-CoCr 0.003" Ground SWAero	WC-Co-Cr 0.003" Ground SWAero
	WC-CoCr 0.003" Unground SWAero

For the 300M series substrates, three samples from each of the NRL and KSC exposed subsets failed, as listed in Table 3-39, while the full data are shown in Figure 3-58.

Table 3-39. Failed Coatings on 300M Substrates

NRLKW Exposed Samples	KSC Exposed Samples
WC-Co 0.003" Ground Hitemco	WC-Co 0.003" Ground Hitemco
WC-Co-Cr 0.003" Ground SWAero	WC-CoCr 0.003" Ground SWAero
WC-CoCr 0.003" Unground SWAero	WC-CoCr 0.010" Ground SWAero

The tables presented above show roughly equivalent performance in terms of protection results from the corrosion cabinets at NRL Key West and Kennedy Space Center. Further, the 0.003"-thick HVOF coated samples accounted for almost all of the failures for each metal substrate, indicating a likely problem with the coating as opposed to a problem with the underlying metal. Also, 3 of the 5 coatings on the 4340 steel and 4 of the 6 coatings that failed on the 300M were EHC.

It is difficult to draw other conclusions that may be statistically significant regarding coating protection from this data set. Inferentially, 0.010"-thick coatings generally perform better than 0.003"-thick coatings, though one 0.010"-thick WC-CoCr coating did fail. There is insufficient data to really tell if grinding the coating affects corrosion performance. The preponderance of the samples that failed to protect the substrate where ground but, as will be discussed below, general corrosion of the coating was worse with unpolished surface samples. Figure 3-51 shows the comparison of 0.003"-thick WC-Co coatings on 4340 steel with those on the left as-deposited and those on the right having been ground. The overall surface corrosion attack on the as-deposited samples is evident

compared to the ground samples. Note that one of these ground samples has had a coating failure.

While a few more Southwest-Aeroservice-applied coatings failed relative to those applied by Hitemco, there was no definitive difference between the coatings deposited by the two vendors.

A final note on substrate protection is the repeat finding that the EHC samples outperformed all others. No EHC coating was breached and there was complete protection of the substrate. Figure 3-52 and Figure 3-53 compare the 0.010"-thick coating types on 4340 and 300M base metals, respectively. The EHC coating integrity and surface finish are significantly better than either of the HVOF coatings.

3.4.5.3.2. Appearance Ratings

The appearance rating is an important attribute in gauging the extent of corrosion on the coating. In most of the samples exposed in this series, the underlying metal substrate was protected but the coating itself was degraded to varying degrees. For instance, the EHC coatings outperformed all other alloys and received the highest appearance rating (10) for seven of the eight EHC samples. The eighth sample received a 9 rating owing to small staining of the surface probably derived from Cd corrosion products running onto the surface. The HVOF-coated samples received varying appearance ratings, generally lower than the EHC samples. Refer to Figure 3-52 and Figure 3-53 for a comparison of surface appearance for the 0.010"-thick coating compositions. Figure 3-55 and Figure 3-56 show the relative appearance rankings for the coatings on 4340 and 300M steels, respectively. Those samples from the KSC cabinet appear to be generally worse with respect to appearance, which would indicate a more aggressive corrosion environment. Overall, the relative rankings are similar for either sample set with the WC-Co indicating somewhat more corrosion than the WC-CoCr.

The as-deposited samples fared the poorest in surface corrosion as noted by both series of data for either the WC-Co or WC-CoCr, and received the lowest appearance ratings. Figure 3-59 depicts the 0.003"-thick WC-Co coating on 300M steel and indicates the overall surface appearance of the as-deposited coatings to be worse. However, as before with the 4340 samples, one of the two ground samples has already failed. There is more general surface attack on samples with an as-deposited coating (at least for samples with a 0.003" coating thickness) but more of the 0.003"-thick ground samples indicated a breach of the coating. The thicker coatings fared better in substrate protection, as expected, but since no 0.010"-thick as-deposited coatings were tested, no definitive conclusion is able to be drawn from this data set when accounting for general coating surface attack AND substrate protection.

3.4.5.4.Conclusions

The following conclusions can be drawn from this supplemental study.

1. 0.010"-thick coatings perform better than 0.003"-thick coatings of any composition in terms of protecting the substrate. See Figure 3-60 and Figure 3-61 for a comparison of the WC-Co coatings.
2. There was no definitive difference between the coatings applied by the two

vendors.

3. EHC coatings outperformed either the HVOF WC-Co or WC-CoCr, regardless of thickness in this corrosion test. See Figure 3-62 and Figure 3-63 for comparisons of 0.010"-thick coatings.
4. For 0.010"-thick coatings, the data implies WC-CoCr coatings show improved performance over WC-Co coatings. Additional studies would be necessary to confirm this conclusion since there was one 0.010"-thick WC-CoCr coating that was breached.
5. The 0.003"-thick coatings are suspect in their ability to protect the substrate steel. While 0.003"-thick EHC in this data set did protect the substrate (one sample only was tested in each location), the LGJTP results with multiple samples being tested showed some 0.003"-thick EHC coatings being breached.

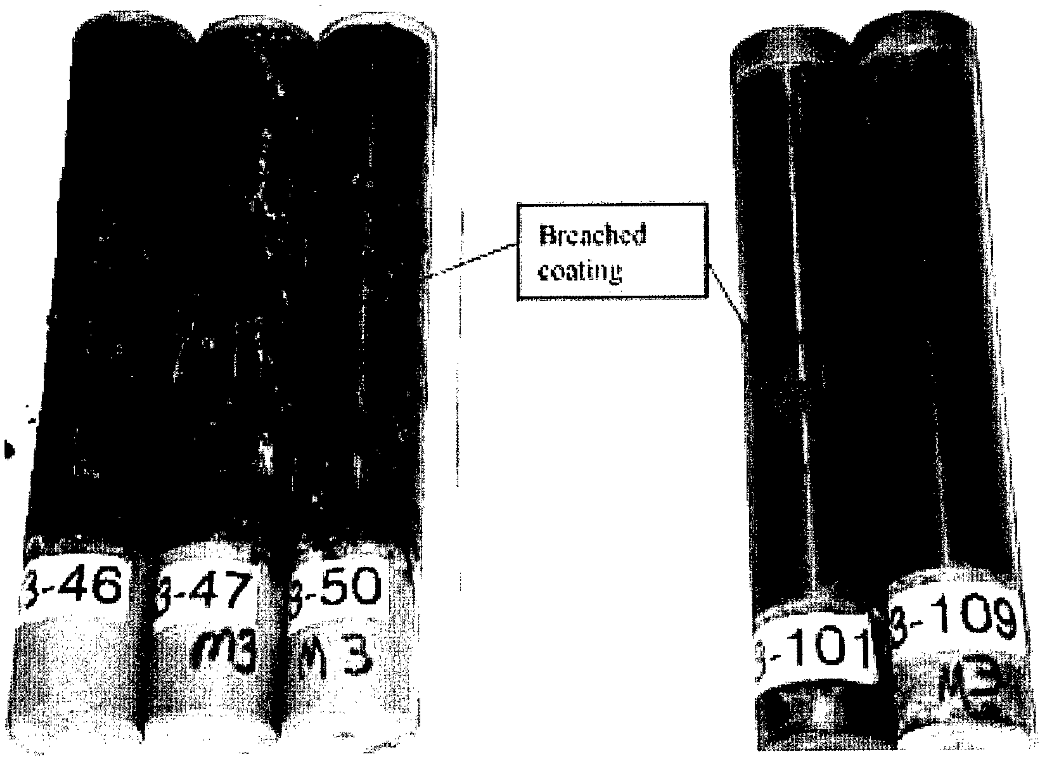


Figure 3-48. HVOF WC-Co Coatings, 0.003" Thick, Ground, on 300M Steel From the LGJTP Tests, Left, and the Supplemental Tests, Right

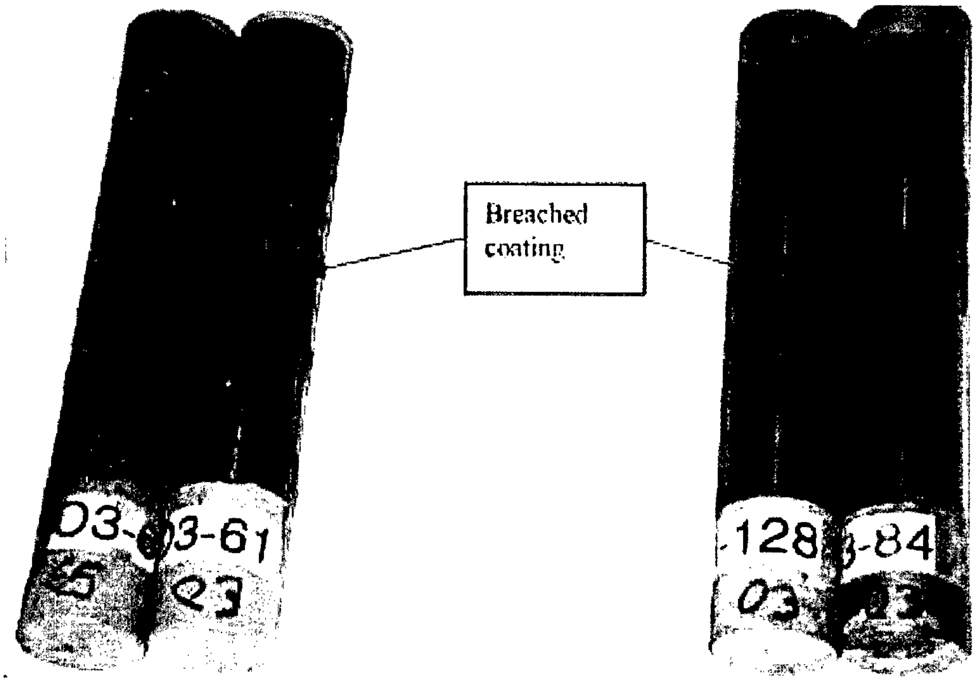


Figure 3-49. HVOF WC-Co Coatings, 0.003"-thick, Ground, on 4340 Steel From the LGJTP Tests

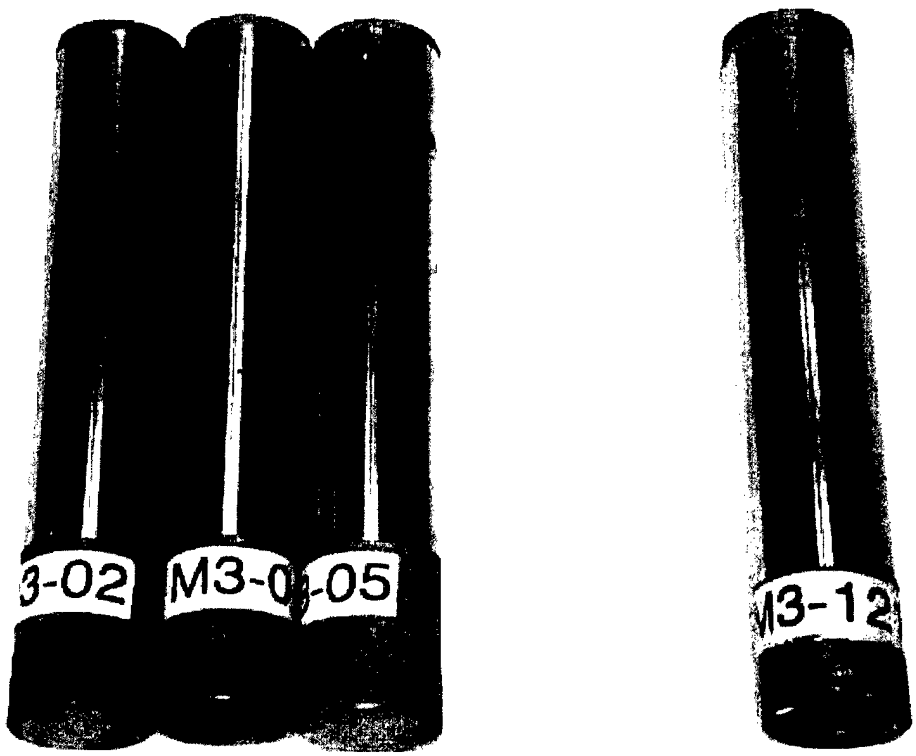


Figure 3-50. EHC Coatings, 0.003"-thick, Ground, on 4340 Steel from the LGJTP Tests, Left, and the Supplemental Tests, Right

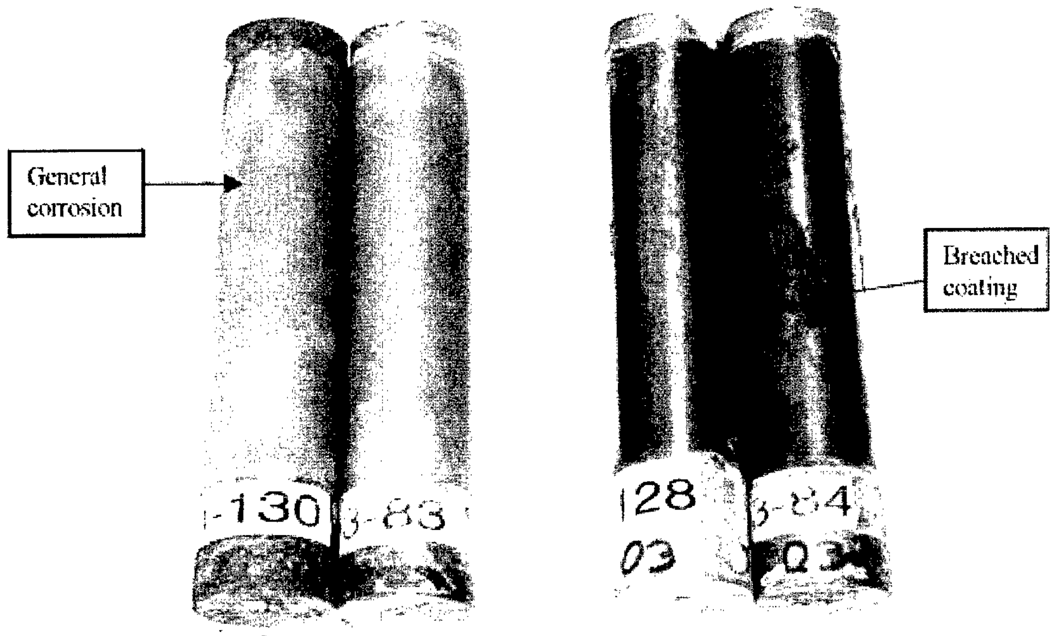


Figure 3-51. HVOF WC-Co Coatings, 0.003"-thick, on 4340 Steel, As-deposited on Left and Ground on Right

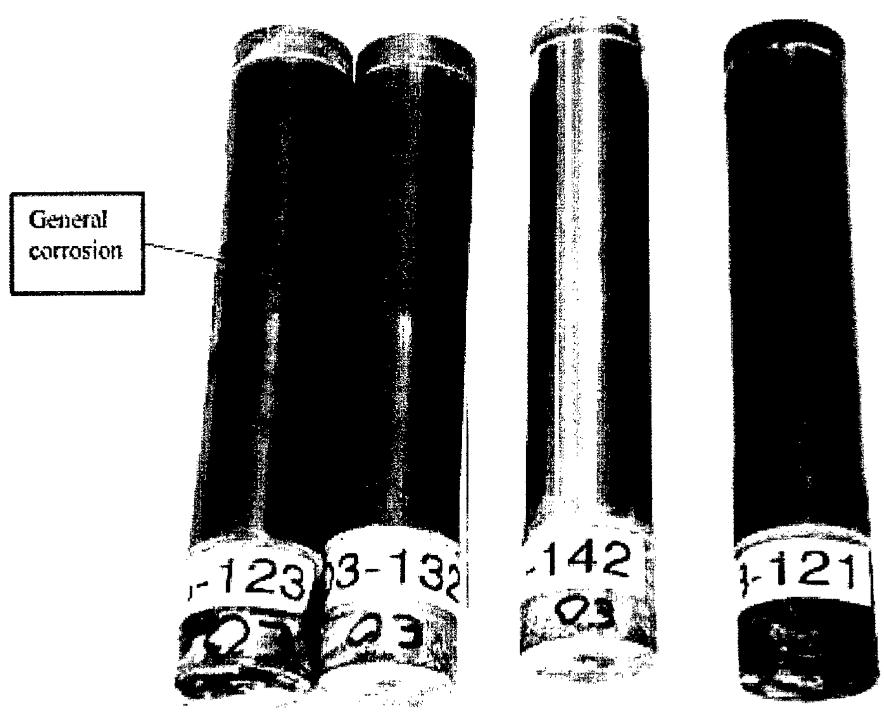


Figure 3-52. Left: WC-Co, 0.010"-thick, Ground. Center: EHC, 0.010"-thick, Ground. Right: WC-CoCr, 0.010"-thick, Ground. All on 4340 Steel Substrates

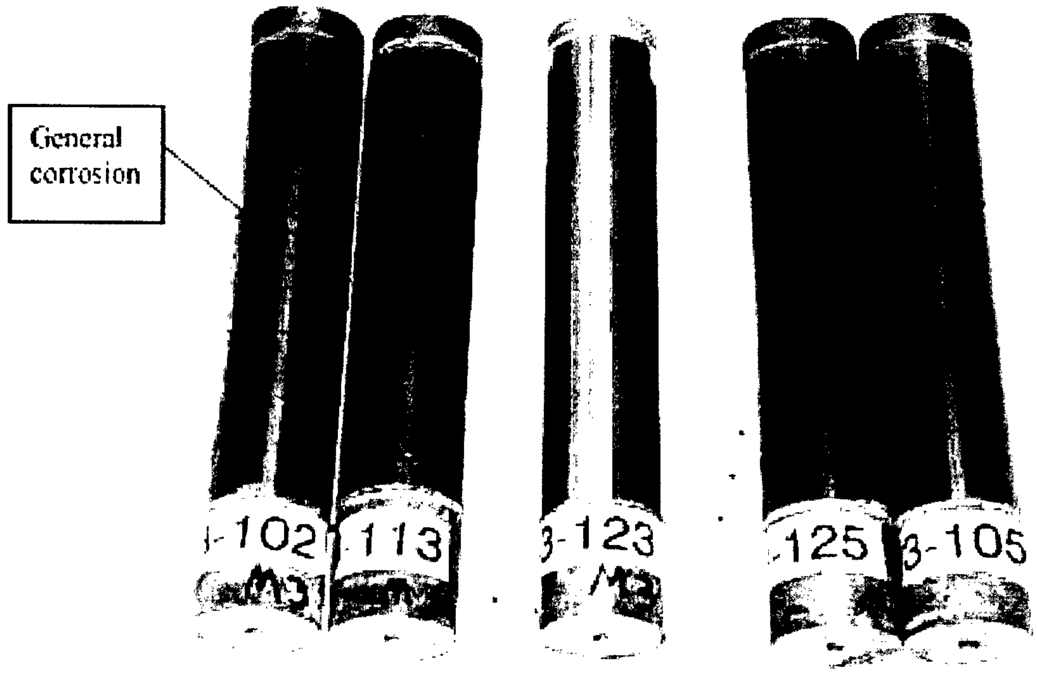


Figure 3-53. Left: WC-Co, 0.010"-thick, Ground. Center: EHC, 0.010"-thick, Ground. Right; WC-CoCr, 0.010"-thick, Ground. All on 300M Steel Substrates

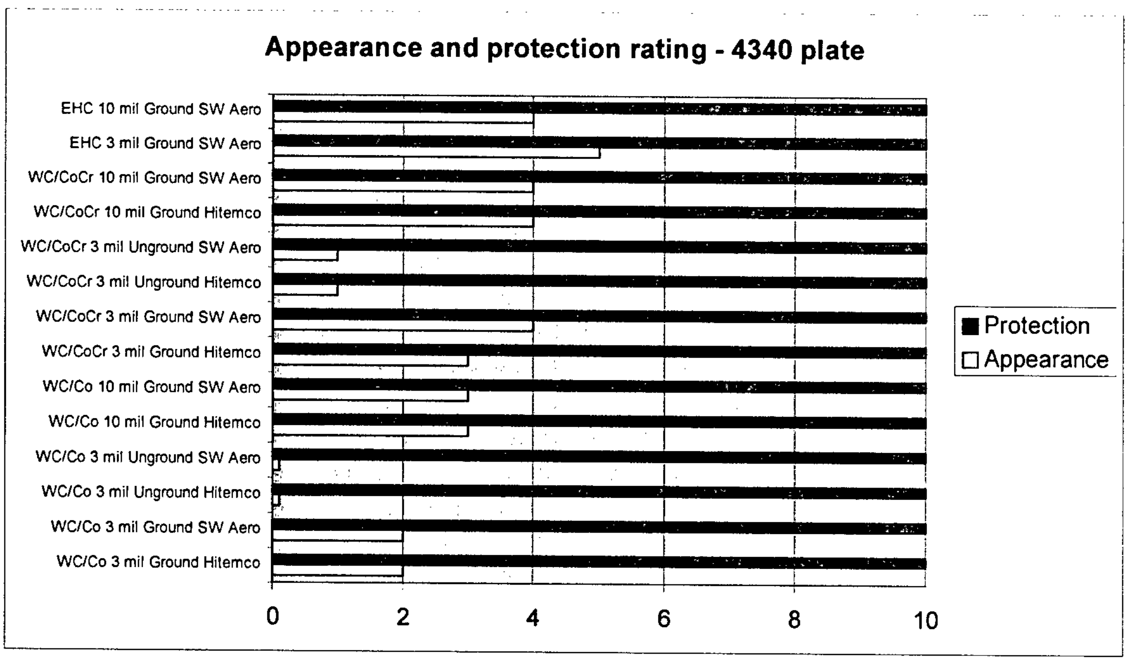


Figure 3-54. Comparison of Appearance and Protection Ratings for 4340 Plate, NRL

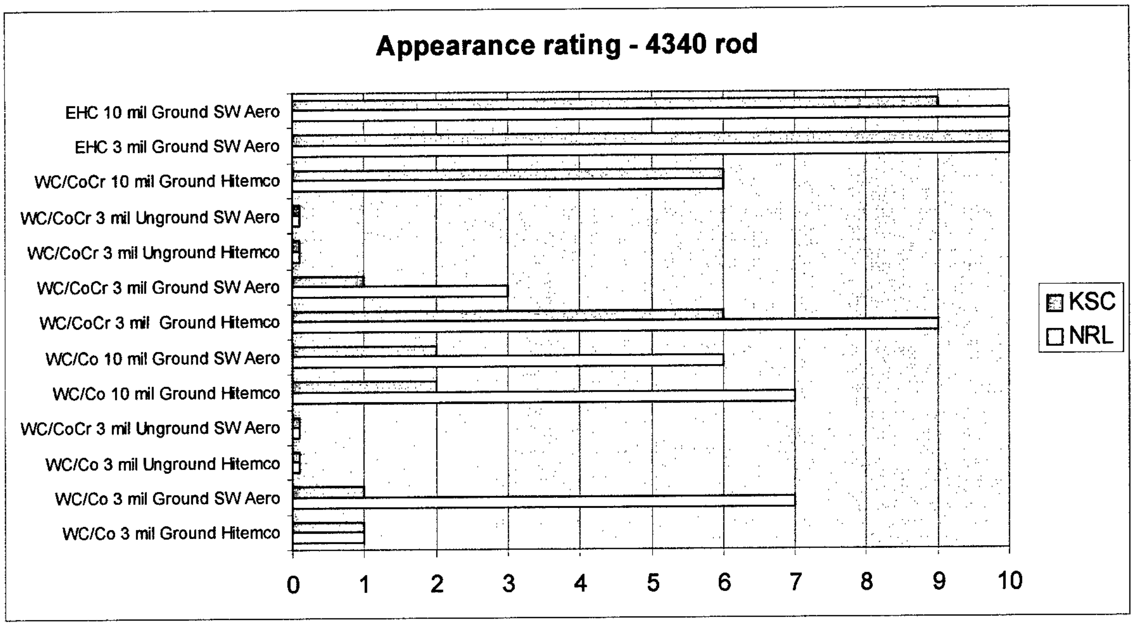


Figure 3-55. Comparison of Appearance Ratings for HVOF and EHC Coatings on 4340 Rod Tested at NRL and KSC

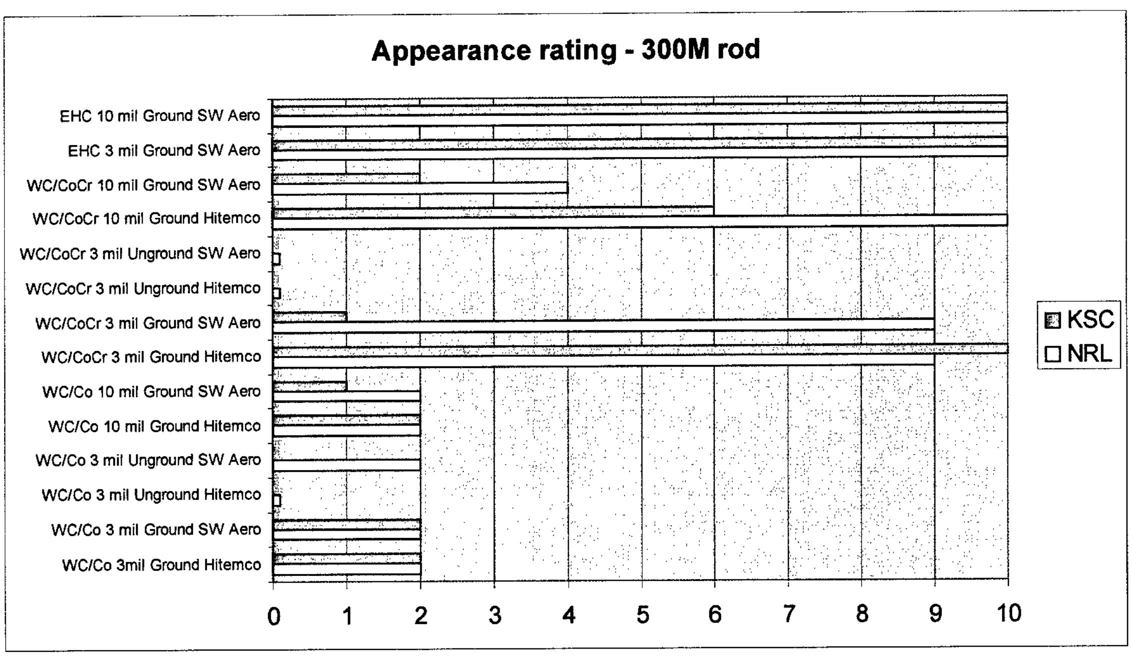


Figure 3-56. Comparison of Appearance Ratings for HVOF and EHC Coatings on 300M Rod Tested at NRL and KSC

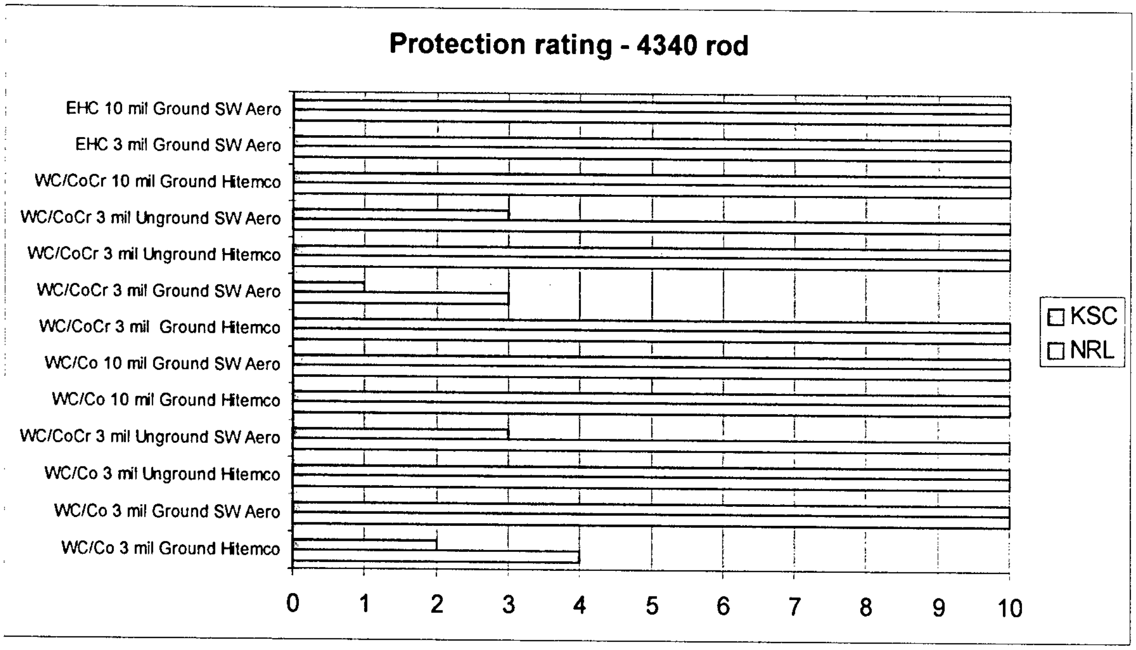


Figure 3-57. Comparison of Protection Ratings for HVOF and EHC Coatings on 4340 Rod Tested at NRL and KSC

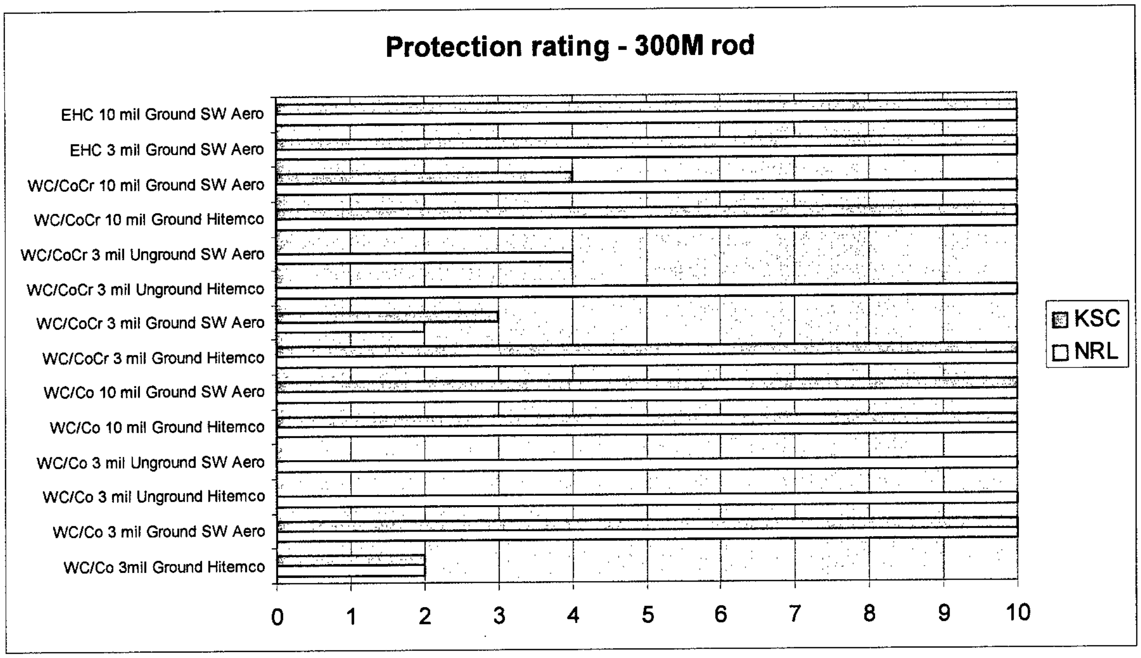


Figure 3-58. Comparison of Protection Ratings for HVOF and EHC Coatings on 300M Rod Tested at NRL and KSC

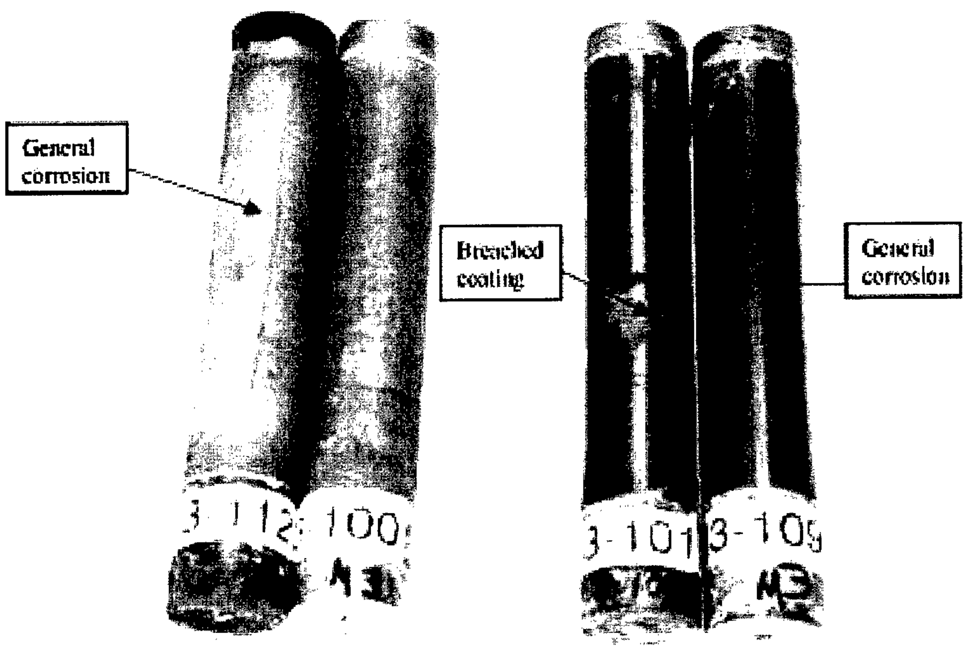


Figure 3-59. WC-Co Coatings, 0.003”-thick, on 300M Steel. Left: As-deposited. Right: Ground

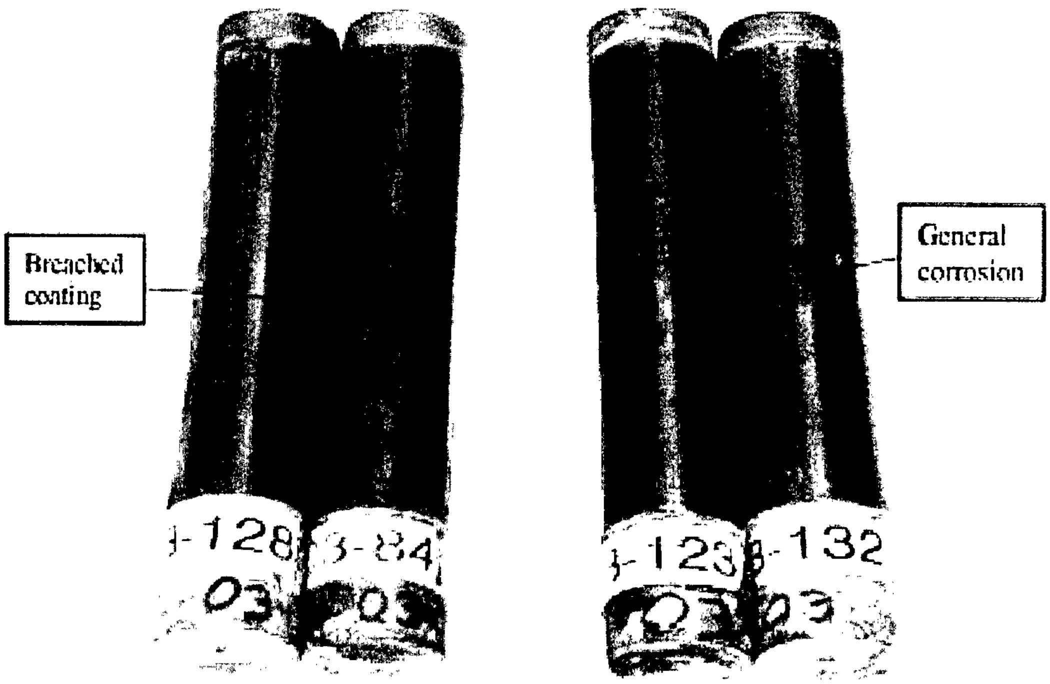


Figure 3-60. WC-Co Coatings on 4340 steel. Left: 0.003"-thick, Ground. Right: 0.010"-thick, Ground

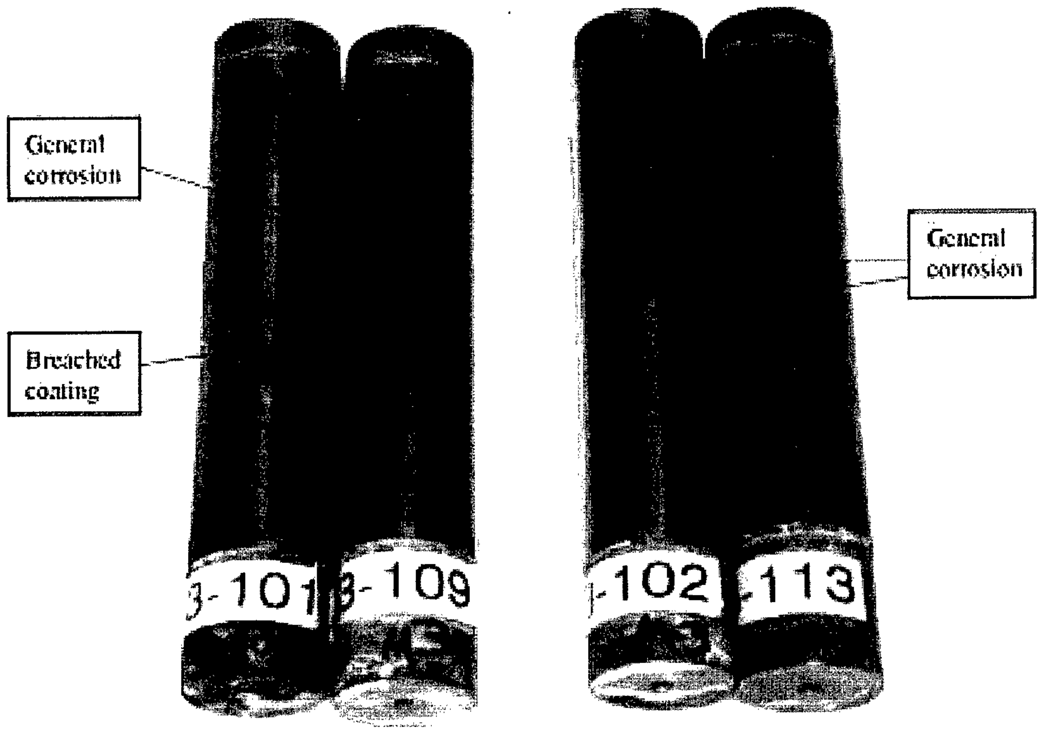


Figure 3-61. WC-Co Coatings on 300M Steel. Left: 0.003"-thick, Ground. Right: 0.010"-thick, Ground

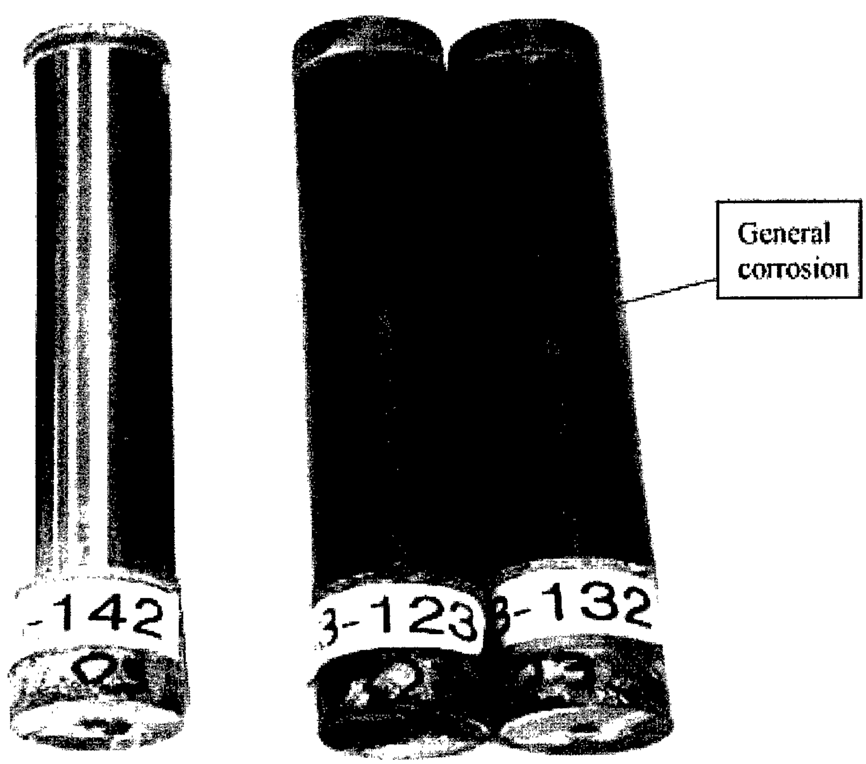


Figure 3-62. Left: EHC Coating, 0.010"-thick, Ground. Right: WC-Co Coating, 0.010"-thick, Ground. All on 4340 Steel

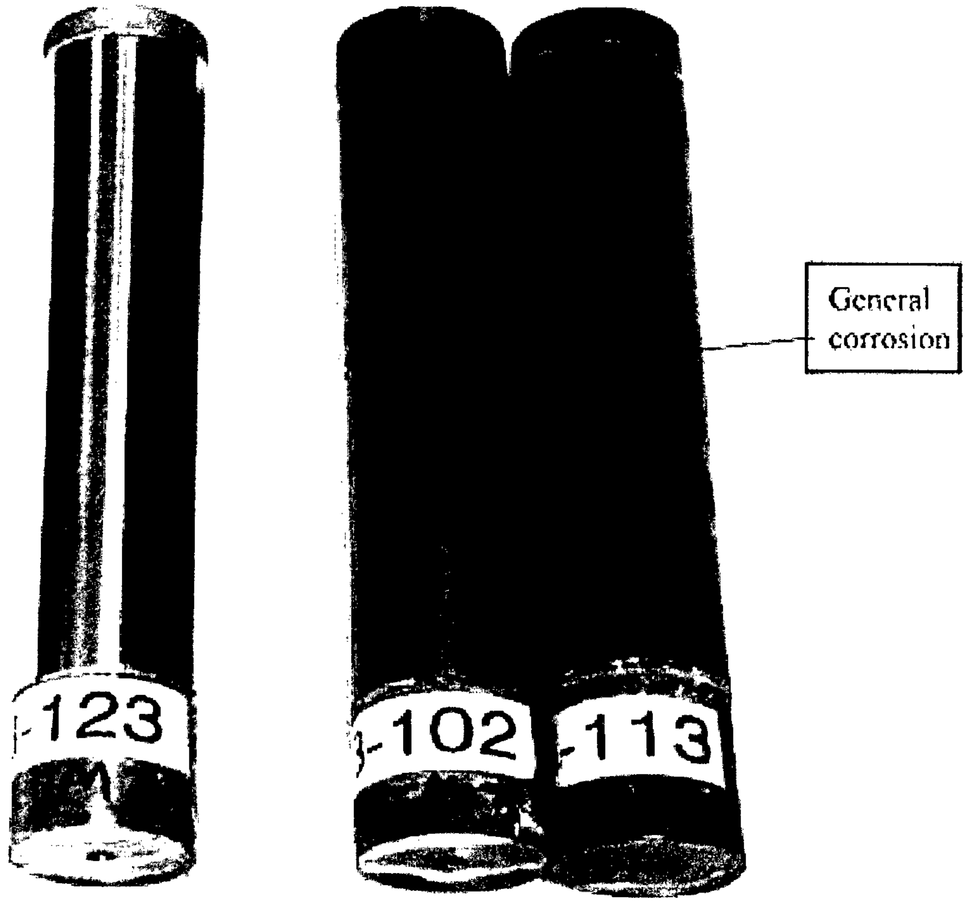


Figure 3-63. Left: EHC, 0.010"-thick, Ground. Right: HVOF WC-Co, 0.010"-thick, Ground. All on 300M Steel

3.4.6. Discussion of overall corrosion results

The data show that the overall corrosion performance of EHC was better than WC-CoCr, which in turn was better than WC-Co. Based on both the Landing Gear JTP and Supplemental testing, it can be concluded that the acceptance criteria from the JTP, namely that the corrosion performance of the HVOF WC-Co and WC-CoCr coatings must equal or exceed that of EHC, was not met. Putting this work into perspective regarding the previous corrosion studies of the HCAT and the studies conducted by others, there are several observations that can be made and issues that should still be addressed.

1. The performance of the EHC coatings in the LGJTP and Supplemental testing was somewhat unexpected in that B117 testing conducted by others on EHC of equivalent thicknesses (see, for example, testing conducted by the Canadian HCAT for their portion of the Landing Gear JTP and testing conducted by Hamilton Sundstrand for the Propeller Hub JTP) showed substantial corrosion after a few hundred hours of exposure. Also note the extremely poor performance of EHC in the three-year atmospheric corrosion tests described in this document. The HCAT plans on conducting analyses of the EHC coatings from these studies and will compare them to coatings from other studies to determine if there are any clear differences that would explain the different performance.
2. The HVOF WC-Co and WC-CoCr coatings do still provide substantial corrosion

protection to the steel substrates evaluated in this study as evidenced by the fact that uncoated steel subjected to B117 is almost completely corroded after several tens of hours exposure. The fact that there was severe undercutting and breaching of many of the HVOF coatings indicates that when these coatings are to be used in service, extreme care should be taken to ensure that the corrosive medium cannot have access to the area where the coating terminates on the base material, such as at an edge. This was proven out by the significantly better performance of the HVOF coatings when the cadmium/chromate coating was used as a sealer for the sample edges instead of the epoxy.

3. Further evidence of the protective nature of the HVOF coatings was illustrated in the results of the cyclic GM9540B testing in which both the EHC and the WC-Co coatings showed virtually no corrosion after 1,000 hours. Although no uncoated steel samples were evaluated in this series of tests, corrosion engineers at NRL indicated that steel such as 4340 would be substantially corroded after only 100 hours in the GM test.
4. In terms of corrosion of the coatings themselves, the WC-CoCr coatings do perform somewhat better than the WC-Co coatings. However, in terms of undercutting and breaching, there was essentially no difference between the coatings, again indicating the importance of ensuring the corrosive medium cannot have access to the coating termination areas on the base material.

3.4.7. Significance

It is difficult to determine the true significance of these data since cabinet corrosion testing is notoriously variable, as is the hard chrome baseline itself. Based on the experience of most aerospace industry team members (e.g. Boeing, Goodrich, Hill AFB) the performance of the Southwest Aeroservice hard chrome appeared to be exceptionally good. However, some significant findings should be noted:

- ❑ Clearly, HVOF coatings provide corrosion resistance compared with uncoated steel. However, given the wide disparity in results between the various tests reported here it is not possible to be sure how they compare with hard chrome coatings typical of those deposited in depots.
- ❑ Since WC-CoCr appears to provide better corrosion resistance that WC-Co, corrosion considerations would suggest that the former be chosen over the latter if both are otherwise acceptable.
- ❑ The data provide evidence that the HVOF coating itself corrodes (especially in the case of WC-Co), whereas for EHC coatings the coating itself is untouched while the substrate corrodes through coating cracks and breaches. This points to a different corrosion mechanism, which is likely to lead to surface roughening or release of micron-sized WC particles over sufficient time. This should be borne in mind when choosing a coating for use in corrosive environments.

3.4.8. Conclusion

HVOF WC-Co and WC-CoCr both fail the JTP acceptance criteria. Note that corrosion comparisons were made against what appeared to be an exceptionally high

quality hard chrome. HVOF coatings may or may not fail tests against hard chrome coatings commonly used in depot or airline repair.

3.5. Wear data

3.5.1. Data summary

Table 3-40. Quick Data Locator (Click on item number to view)

Item	Item number
L12 Matrix Data – Fretting	Table 3-49
L12 Test Matrix Data - Sliding Wear	Table 3-50
L8 DOE Data	Table 3-51 - Table 3-54
Fretting wear data	Figure 3-70, Figure 3-71
Sliding wear data – L12 matrix	Figure 3-72, Figure 3-73
Sliding wear data – final L8 matrix, including average data and data for the metal bushing baseline and all half-replicates	Figure 3-74, Figure 3-75, Figure 3-79 - Figure 3-84
Statistical analysis of L8 data	Figure 3-76 - Figure 3-78

The full data set is provided in Appendix 4 of the JTR [3.1].

3.5.2. Rationale

Prior experience in the aircraft industry (and in other industries) has been that the wear performance of components coated with WC-Co or WC-CoCr exceeds that of hard chrome. It is primarily for this reason that companies such as Boeing have substituted these HVOF coatings in place of hard chrome for specific spot applications on components where hard chrome performance in the field was found to be inadequate. (These problem-area applications now total more than a hundred.)

Wear is a very complex phenomenon and depends on a great many factors that are specific to each engineering system. Recognizing this, true measurements of performance were designed to be made in Part 2 of the Landing Gear Joint Test Protocol, using full-scale rig and flight testing. The purpose of the measurements made in Part 1 was to determine which factors (coating material, surface finish, test conditions, etc.) have the most impact on wear performance and therefore must be most carefully controlled.

Landing gear applications of hard chrome include both long-stroke sliding wear experienced by landing gear utility actuators and inner cylinders, and short stroke, oscillating wear (dithering and fretting) experienced by pins and hydraulic cylinders during ground operations. Testing was designed to evaluate both of these conditions.

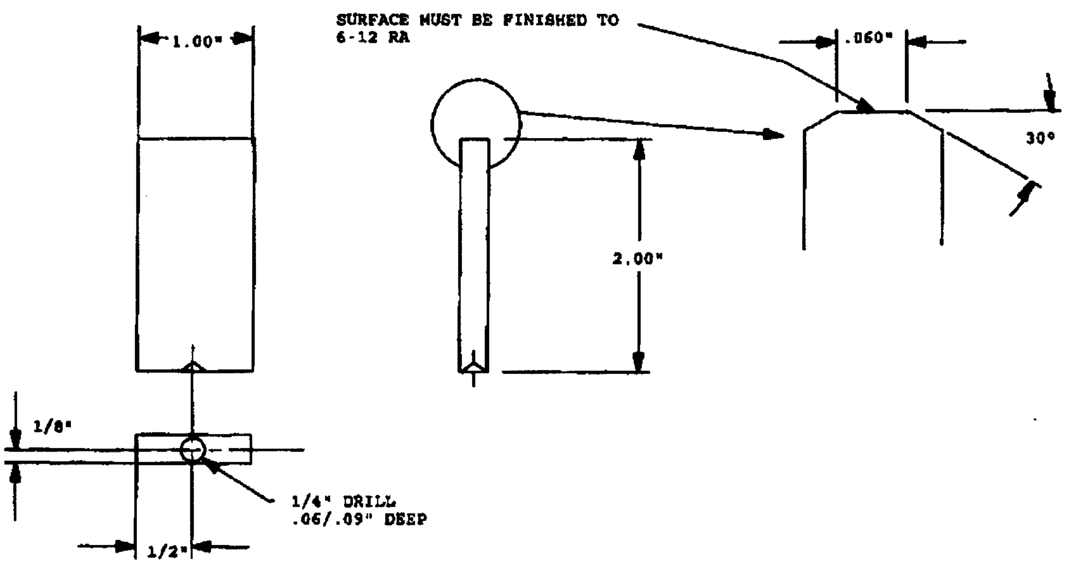
3.5.3. Specimen fabrication

3.5.3.1.Fretting specimens

Fretting blocks and shoes were made of 4340 plate stock according to the design shown in Figure 3-64. In this design, the fretting shoe (Figure 3-64a) is the same 1" width as the fretting block (Figure 3-64b). Only the shoe was coated.

The block and shoe materials are summarized in Table 3-41.

a.



b.

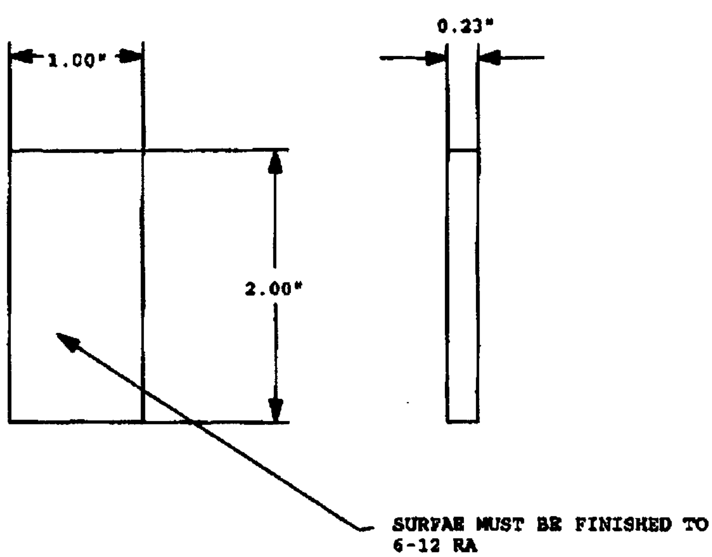


Figure 3-64. a) Fretting Block; b) Fretting Shoe

Table 3-41. Wear Test Materials and Coatings – Fretting (Fretting blocks uncoated, 4340 shoe coated)

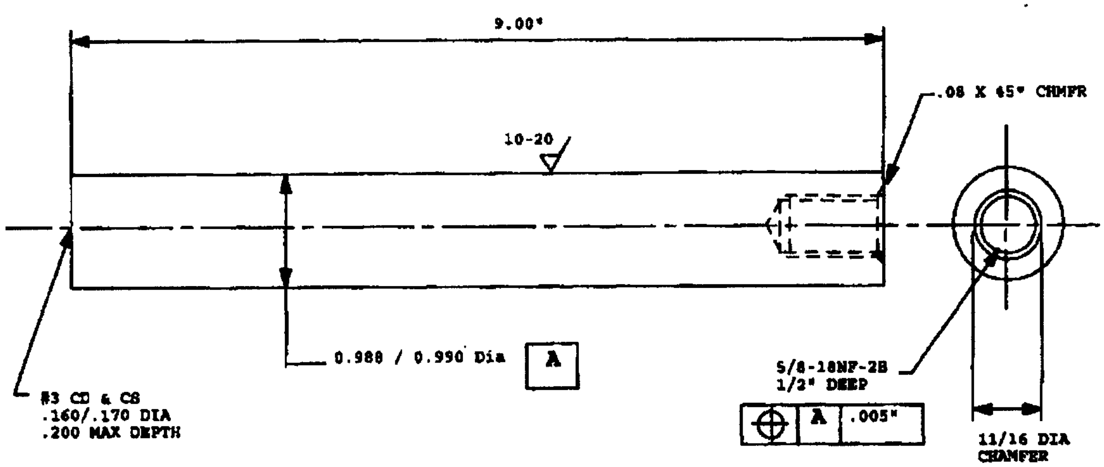
Fretting Shoe Coating	Thickness (inch)	Fretting Block
Hard chrome plate	0.003, 0.010	4340 steel
HVOF WC-17Co (Diamalloy 2005 powder)	0.003, 0.010	Nitrile seals in 4340
HVOF WC-10Co-4Cr (SM5847 powder)	0.003, 0.010	

3.5.3.2. Sliding wear specimens

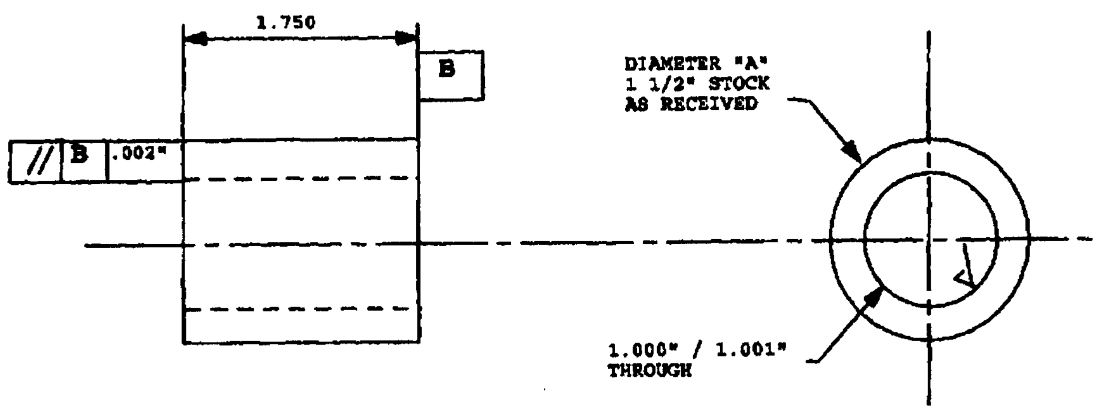
The design of the sliding wear specimens is shown in Figure 3-65. Bushings were made of various materials. All wear rod specimens were fabricated from 4340 round bar, as follows:

- 1" diameter, 9" long
- Tensile strength and heat treat – 260-280 ksi per MIL-H-6875
- Shot peen – 8-10A, S230, wrought steel shot, per AMS 2432, computer controlled, 100% coverage, except a 0.75" section at one end of the rod
- Grit blast prior to coating – Specimens were gripped on the non-peened area and a 5" section grit blasted:
  - For EHC with 180-220 grit alumina or glass beads
  - For HVOF coating with 54 grit alumina at 60 psi at 90° angle of impingement, per MIL-STD-1504.
- Coating – per methodology in Section 3.6.4 below
  - Thickness – final thickness 0.003" and 0.010" (see Table 3-42). Coatings were deposited 0.002-0.003" thicker to allow for final grinding.
- Embrittlement relief heat treat - 375°F for EHC plated samples only.
- Grind after coating
  - For EHC low stress grind to 16μ" finish per MIL-STD-866
  - For HVOF low stress grind to 8μ" finish per BAC 5855

a)



b)



c)

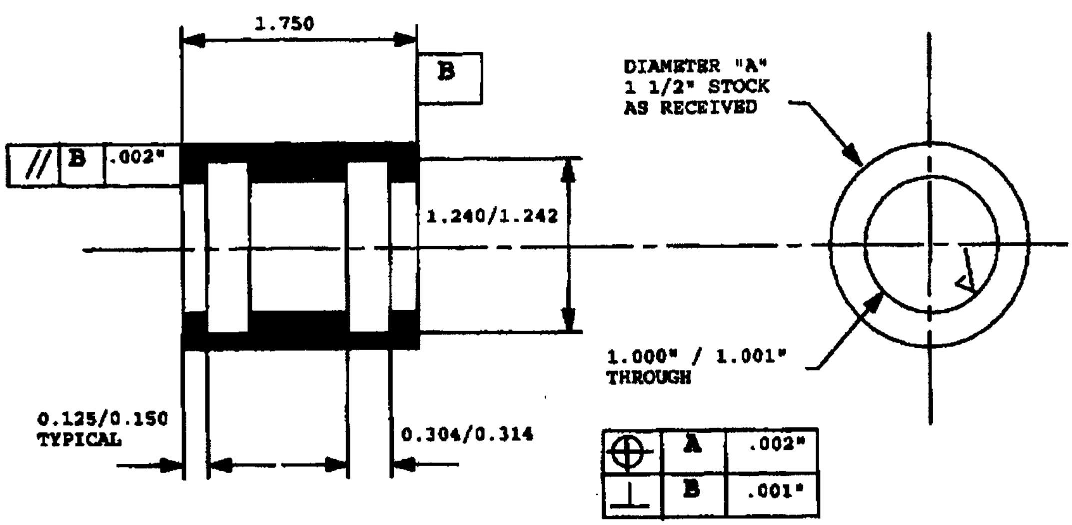


Figure 3-65. Wear Test Rods and Bushings - a) Rod, b) Straight Bushing, c) Seal Groove Bushing

3.5.4. Coating deposition methodology

Table 3-42. Wear Test Materials and Coatings - Sliding. (Piston coated, bushing uncoated)

Piston/coating material	Thickness (inch)	Coating vendor and specification	Bushing material
Hard chrome plate	0.003, 0.010	Southwest Aeroservice, Tulsa, OK; QQ-C-320B, Boeing-approved specification	4340 steel
HVOF WC-17Co (Diamalloy 2005)	0.003, 0.010	NADEP Cherry Point; HCAT specs.	Al-Ni bronze
HVOF WC-10Co-4Cr (SM5847)	0.003, 0.010	NADEP Cherry Point; HCAT specs.	Anodized 2024-T3 aluminum
			Nitrile seal
			Karon B seal

Coating materials and thicknesses tested are summarized in Table 3-42.

Samples were coated as follows:

- Hard chrome – standard Boeing specifications
- WC-Co – DiamondJet gun, per HCAT specifications
  - Powder – Diamalloy 2005
  - Fuel – Hydrogen
- WC-CoCr – DiamondJet gun, per HCAT specifications
  - Powder – Sulzer Metco 5847
  - Fuel – Hydrogen
- Aluminum anodize – by Southwest Aeroservice per MIL-P-25732 B.

3.5.5. Test methodology

In consonance with the aim of determining performance factors rather than measuring performance itself, the wear evaluation tests were made in the form of Design of Experiment (DOE) protocols, with most of the testing being done for sliding wear, which has the broadest application. Test conditions were designed to obtain measurable results in a short time rather than to duplicate service conditions. This experimental design incorporated the following:

- A pre-DOE matrix to establish the test conditions. The test conditions in this matrix were to be modified by results in order to determine the range of test conditions necessary to provide reasonable, measurable ranges of wear rates for

the material combinations in tests typically averaging no more than 48 hours. This information was used to confirm or reassign specific values to the conditions for the design factors in the first L12 DOE test matrix.

- An L12 matrix to evaluate the major potential wear factors for both fretting and sliding wear, and establish which factors were the most significant and should be evaluated in more detail in the subsequent L8 DOE matrix.
- An L8 matrix to quantify the relative contributions to sliding wear performance of the major wear factors identified in the L12 matrix. Fretting wear was not incorporated in the L8 matrix.

3.5.5.1. Fretting

Specification: No existing public standard. These tests followed the GE Aircraft Engines fretting test method used for engine components.

Modifications: For some tests the fretting block was modified to incorporate a section of seal material.

Significance: Short-stroke, unlubricated wear is typical of the conditions experienced by pins and hydraulics during ground operations.

Sample types: Blocks and shoes.

Sample materials: 4340

Sample heat treat: 260-280 ksi UTS

Coatings: EHC, WC-Co, WC-CoCr, 0.003" and 0.010" thick.

Lubrication: MIL-H-83262 hydraulic fluid (Royco 782)

Test equipment: Test equipment is illustrated schematically in Figure 3-66. Testing was done in a standard vertical fatigue machine adapted to provide a side load via the shoe, as illustrated in the figure.

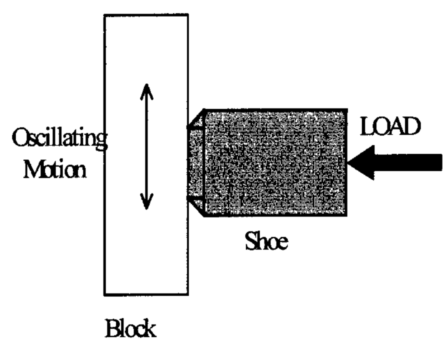


Figure 3-66 Cross-sectional Schematic of Fretting Wear Test

Test description:

Tests were run with the block set in a specially-designed holder on a standard closed-loop MTS machine. The shoe was pressed against the block with a normal load, P_N, applied by a dead weight system. Lubrication, where needed, was supplied by dripping from above the fretting region. Test conditions (loads, speeds, lubrication, etc.) are given in the test matrices. Wear of the coated shoe and uncoated block was measured by weight change.

3.5.5.2. Sliding wear

Specification: No existing standard.

Modifications: None

Significance: Long-stroke actuation typical of hydraulic cylinder rods in landing, takeoff, and ground operations.

Sample types: Rods: 1" round rod, 9" long; 1.5" OD, 1" ID bushings.

Sample materials: Rods: 4340 steel heat treated to 260 – 280 ksi UTS.

Bushings: 4340 steel heat treated to 160-180 ksi; AMS 4640 Al-Ni-bronze rod in the TQ50 or equivalent HR50 condition (hardness HB 201-248); anodized 2024 Al (MIL-A-8625, Type 3, Class I).

Seals: Nitrile T seals type 7214-FT-160-T from Green Tweed (MIL-HDBK-695C).

Liners: Karon B from Kamatics Corp. (filled phenolic 0.015" thick).

Coatings: EHC, WC-Co, WC-CoCr, 0.003" and 0.010", ground to 16μ" for EHC and to 8μ" Ra for HVOF.

Lubrication: MIL-H-83262 hydraulic fluid (Royco 782)

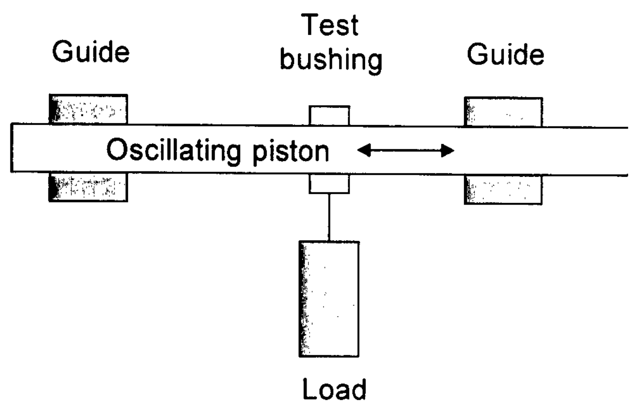


Figure 3-67. Cross-sectional Schematic of Piston and Bushing Oscillating Wear Test

Test equipment: Test equipment is illustrated schematically in Figure 3-67 and shown photographically in Figure 3-68. The test rod was oscillated on four bearings, driven by a hydraulic actuator via a load cell to measure the drive load, P_{drive}. Normal load was applied to the bushing via a spring assembly and load cell so as to create a wear couple between the rod and the bushing. The lubricant was supplied at the bushing from a suspended bag through a small tube and a constricting valve that controlled the drip rate.

Test description:

For both sliding wear and fretting the coefficient of friction was measured as

$$\mu = [P_{drive(max)} - P_{drive(min)}]/2\ P_N$$

Test conditions were as defined in the test matrices. Hydraulic fluid was added to permit fully-lubricated, starved-lubricated, or unlubricated testing. Under "Full" lubrication fluid was added throughout the test, while under "partial" lubrication lubricant was added only for the first hour of the test, then turned off for the remainder of the test.

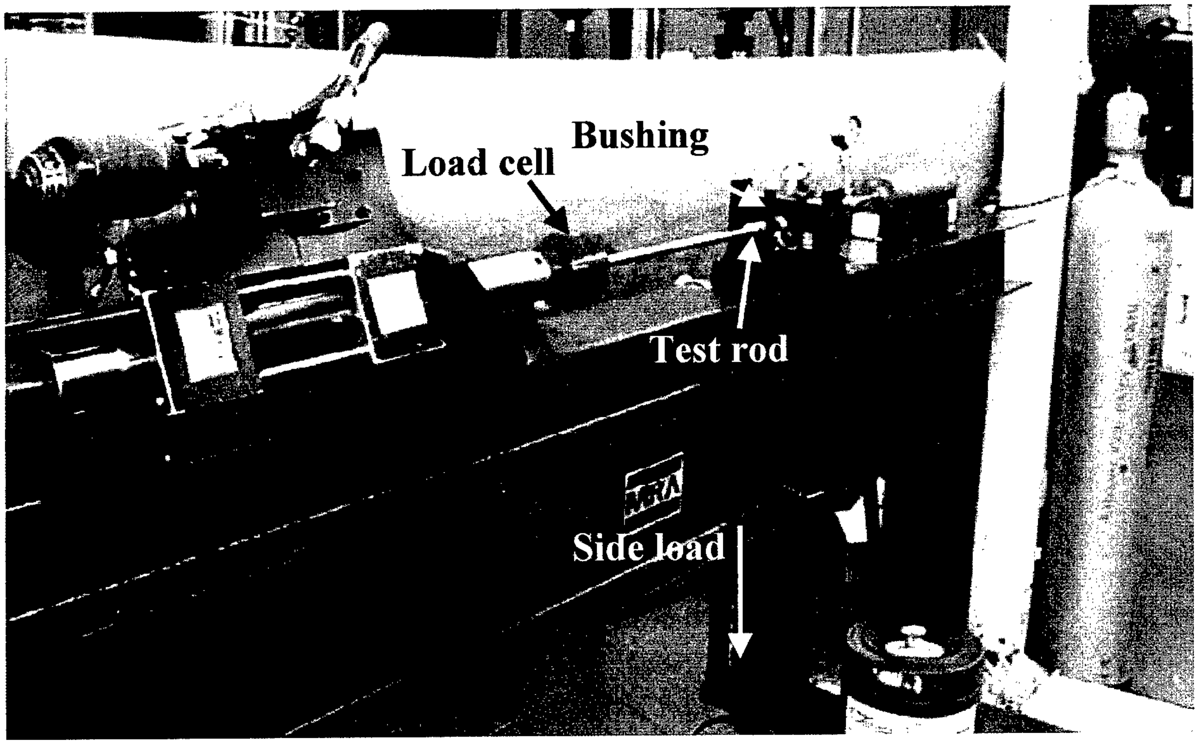


Figure 3-68. Sliding Wear Test Equipment

For the nitrile seal rod/bushing tests, a pair of standard T-seals was assembled into a grooved bushing. These seals were pre-soaked in hydraulic fluid for 24 hours prior to assembly to permit any absorption to fluid to occur. After assembly with the rod, the seals were energized by filling the inter-seal region with hydraulic fluid from a reservoir and pressurizing to 3000 psi with a nitrogen bottle through a small orifice in the bushing. For the partial lubrication tests in the L12 and L8 phases, the test was stopped and depressurized after 1 hour and disassembled to drain the lubricant. The rod and bushing cavity were wiped with a clean, dry rag to remove any excess lubricant, reassembled, and repressurized with dry nitrogen to re-energize the seals, and the test was then restarted.

Wear was judged in two ways:

- Weight loss – this was found to be an unreliable method since small amounts of lubricant trapped in the center hole or thread of the rod caused large errors – up to 0.010 gm.
    - Measurement accuracy was tested by making a series of measurements:
        - 0.00006 gm for WC-Co
        - 0.00011 gm for metals and hard chrome
        - 0.00063 for seals and anodized Al
- Visual appearance against standards – this method was used to overcome the problems caused by weight measurement errors due to trapped fluids. The standards are shown in Figure 3-69 and described in Table 3-43. A visual ranking was assigned by the closest match to the standards.

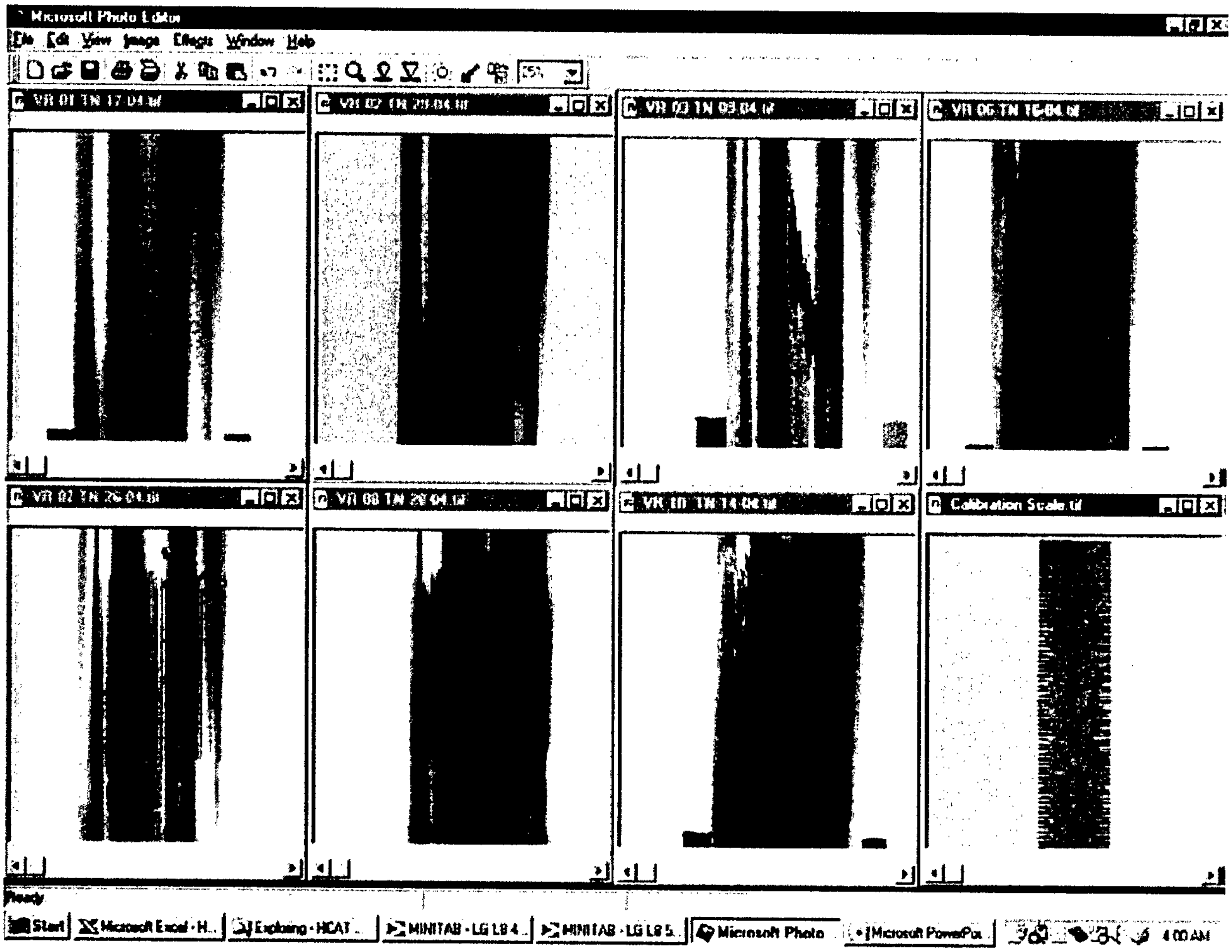


Figure 3-69. Visual Ranking Standards for Rods, VR 01 to VR 10

Table 3-43. Description of Visual Wear Ranking

Rank	Description
1	No visible wear scar
2	Slight burnishing of circumferential grinding marks on rod
3	Small, isolated longitudinal wear patches; circumferential marks still partially visible
4	Larger, more extensive longitudinal marks
5	General longitudinal marking; circumferential grind lines obliterated
6	Extensive wear regions, some metal transfer may have occurred
7	Some deep longitudinal grooving within large general wear scars
8	Wear scars cover entire stroke length from approximately 10:00 to 2:00 on the rod
9	Rating 8 plus some longitudinal grooving
10	Rating 8 plus extensive, deep longitudinal grooving, metal transfer.

3.5.5.3. Test matrices

Table 3-44. Matrix for Pre-DOE – Fretting Tests Run

Test No.	DoE Expt. No.	Wear Test	Block or Bushing	Coating	Load, lbs	Coating Finish	Lube
1	pre-trial	Fretting	4340	WC-10Co-4Cr	72	16	no
2	pre-trial	Fretting	4340	Chrome	72	16	no
3	pre-trial	Fretting	4340	WC-17Co	72	16	no
4	pre-trial	Fretting	4340	Chrome	288	16	no
5	pre-trial	Fretting	4340	WC-17Co	288	16	no
6	pre-trial	Fretting	4340	WC-17Co	288	16	yes
7	pre-trial	Fretting	Nitrile	WC-17Co	40	16	yes

Table 3-45. Matrix for Pre-DOE (Design of Experiment) - Sliding

Test No.	DoE Expt. No.	Wear Test	Block or Bushing	Coating	Load, lbs	Coating Finish	Lube
13	pre-trial	Bushing	4340	WC-10Co-4Cr	72	16	no
14	pre-trial	Bushing	4340	Chrome	72	16	no
15	pre-trial	Bushing	4340	WC-17Co	72	16	no
16	pre-trial	Bushing	4340	Chrome	144	16	no
17	pre-trial	Bushing	4340	Chrome	36 or 288	16	no
18	pre-trial	Bushing	4340	Chrome	72	4	no
19	pre-trial	Bushing	4340	Chrome	288 or144	16	yes
20	pre-trial	Bushing	4340	WC-17Co	288 or144	16	yes
21	pre-trial	Bushing	Nitrile	Chrome	40	16	no
22	pre-trial	Bushing	Nitrile	Chrome	40	16	yes
23	pre-trial	Bushing	Nitrile	WC-17Co	40	16	yes
24	pre-trial	Bushing	Nitrile	WC-17Co	40	16	no

Table 3-46. **L-12 Design of Experiment Matrix for Fretting**

Design Factors	2	3	4	5	6	7	8	9	10
DoE Std. Order	Block or Bushing	Rod/Shoe Coating	Load (lbs)	Coating Finish	Hydraulic Fluid Lubric'n	Stroke (inches)	Frequency (cpm)	Cycles (n)	Temp (Deg F)
1	4340	Chrome	72	4	partial	0.01	600	720,000	70
2	4340	Chrome	72	4	full	0.05	240	360,000	200
3	4340	WC-17Co	288	8	partial	0.01	600	360,000	200
4	Nitrile	Chrome	72*	8	partial	0.05	240	720,000	70
5	Nitrile	WC-17Co	72	8	full	0.05	240	720,000	200
6	Nitrile	WC-17Co	72*	4	full	0.01	600	360,000	70

*Originally assigned at 288 lb P_N.

Table 3-47. **L-12 Design of Experiment Matrix for Bushings/Liners**

Design Factors	2	3	4	5	6	7	8	9	10
DoE Std. Order	Block or Bushing	Rod/Shoe Coating	Load, lbs	Coating Finish	Hydraulic Fluid Lubric'n	Stroke (inches)	Frequency (cpm)	Cycles (n)	Temp (Deg F)
7	4340	WC-17Co	288	4	partial	1.0	30	108,000	200
8	4340	WC-17Co	72	8	full	1.0	90	108,000	70
9	4340	Chrome	288	8	full	0.1	30	54,000	70
10	Nitrile	WC-17Co	72	4	partial	0.1	30	54,000	70
11	Nitrile	Chrome	288	4	full	0.1	90	108,000	200
12	Nitrile	Chrome	72	8	partial	1.0	90	54,000	200

Table 3-48. L-8 Wear Test Matrix. Note: each test condition was run twice (A and B)

		Design factors			
		C	B	A	D
Test No.	DOE Expt. No.	Coating	Bushing	Cycles	Normal Load, lb.
49 A&B	L8-01	Chrome	4340	80K	72
50 A&B	L8-02	Chrome	4340	240K	288
51 A&B	L8-03	Chrome	AMS 4640*	80K	288
52 A&B	L8-04	Chrome	AMS 4640	240K	72
53 A&B	L8-05	WC-17Co	4340	80K	288
54 A&B	L8-06	WC-17Co	4340	240K	72
55 A&B	L8-07	WC-17Co	AMS 4640	80K	72
56 A&B	L8-08	WC-17Co	AMS 4640	240K	288
1st L8 Half Replicate (a)					
57 A&B	L8-5a	WC-10Co-4Cr	4340	80K	288
58 A&B	L8-6a	WC-10Co-4Cr	4340	240K	72
59 A&B	L8-7a	WC-10Co-4Cr	AMS 4640	80K	72
60 A&B	L8-8a	WC-10Co-4Cr	AMS 4640	240K	288
2nd L8 Half Replicate (b)					
61 A&B	L8-3b	Chrome	Anodized Al	80K	288
62 A&B	L8-4b	Chrome	Anodized Al	240K	72
63 A&B	L8-7b	WC-17Co	Anodized Al	80K	72
64 A&B	L8-8b	WC-17Co	Anodized Al	240K	288
3rd L8 Half Replicate (c)					
65 A&B	L8-3b	Chrome	Nitrile seal	80K	288
66 A&B	L8-4b	Chrome	Nitrile seal	240K	72
67 A&B	L8-7b	WC-17Co	Nitrile seal	80K	72
68 A&B	L8-8b	WC-17Co	Nitrile seal	240K	288
4th L8 Half Replicate (d)					
69 A&B	L8-3d	Chrome	Karon B liner	80K	288
70 A&B	L8-4d	Chrome	Karon B liner	240K	72
71 A&B	L8-5d	WC-17Co	Karon B liner	80K	72
72 A&B	L8-6d	WC-17Co	Karon B liner	240K	288
5th L8 Half Replicate (e)					
73 A&B	L8-1e	Chrome	Karon B liner	80K	72
74 A&B	L8-2e	Chrome	Karon B liner	240K	288
75 A&B	L8-3e	WC-10Co-4Cr	Karon B liner	80K	288
76 A&B	L8-4e	WC-10Co-4Cr	Karon B liner	240K	72
77 A&B	L8-5e	Chrome	AMS 4640	80K	288
78 A&B	L8-6e	Chrome	AMS 4640	240K	72
6th L8 Half Replicate (f)					
79 A&B	L8-1f	Chrome	Nitrile seal	80K	72
80 A&B	L8-2f	Chrome	Nitrile seal	240K	288
81 A&B	L8-3f	WC-10Co-4Cr	Nitrile seal	80K	288
82 A&B	L8-4f	WC-10Co-4Cr	Nitrile seal	240K	72
	X2 for each TOTAL = 68		* Al-Ni Bronze		

3.5.6. Test results

3.5.6.1. Pre-DOE

The pre-DOE matrix was not a design-of-experiment matrix , but was a screening test designed simply to determine general behavior and to decide on the test conditions for subsequent testing. It led to the following conclusions:

Fretting tests:

No meaningful conclusions on relative coating behavior could be drawn from the pre-DOE data. However, test conditions were determined:

- For seal tests it was found that a load of 40 lb compressed the seal, leaving only about 0.001" between the rod (or in fretting tests the shoe) surface and the bushing (or block in fretting tests). Above this load the rod (or shoe) touched the bushing (or block). **Therefore 40 lb was the maximum test load used in all pre-DOE seal tests (see Table 3-44 and Table 3-45).**
- The 288 lb. load resulted in greater wear than did the 72 lb. load.
- Unlike the rod/bushing tests, it was possible to run fretting tests in the dry, unlubricated condition at either load without experiencing unstable tests.

Sliding wear tests:

- The dry, unlubricated test was much more severe than the lubricated test, even at low load. This test did not appear to distinguish between the three coatings, and was unsuitable for the L12 DOE.
- On the other hand, a continuous flooded lubricant test did not adequately distinguish among the coatings; nor did a test protocol in which the rod was flooded for 1 hr. (5,400 cycles) and then the lubricant shut off.
- A qualitative discrimination between the EHC and WC-17Co coatings was obtained using a slow drip/shutoff test protocol.
- A 288 lb. normal load provided more significant discrimination of coating performance than did a 72 lb. normal load.
- In general, initial friction values for HVOF coatings were higher than for EHC plating.
- Weight loss had to be measured to 4 decimal places to detect any post-test differences. This was a problem, since it was very easy for lubricant to become trapped in centering holes and threads.

Note that the test conditions chosen for subsequent testing do not represent true service conditions, but rather conditions for obtaining a measurable difference in wear behavior between hard chrome and HVOF coatings.

3.5.6.2. L12 fretting tests

Fretting was measured only in the L-12 DOE matrix.

The results are shown in Table 3-49 and in Figure 3-70 and Figure 3-71. Note that, since this was a DOE matrix, each point corresponds to a different set of conditions, as shown in the matrix of Table 3-46.

Table 3-49. L12 Matrix Data – Fretting

TEST NUMBER	TEST SERIES	BLOCK WEIGHT CHANGE	SEAL WEIGHT CHANGE	SHOE WEIGHT CHANGE	WEAR RANKING (SHOE)	Wear couple block/shoe
1-04	1A	0.0001		0.0003	2	4340/EHC
3-04	1B	0.0012		0.0008	2	4340/EHC
12-04	2A	0.0006		0.0016	2	4340/EHC
13-04	2B	-0.0052		-0.0050	2	4340/EHC
15-04	3A	0.0034		0.0049	2	4340/WC-Co
20-04	3B	-0.0022		0.0011	2	4340/WC-Co
4-04	4A		0.0102	0.0078	2	Nitrile/EHC
8-04	4B		-0.0759	0.0038	2	Nitrile/EHC
22-04	5A		-0.0171	0.0114	1	Nitrile/WC-Co
30-04	5B		0.0462	0.0133	1	Nitrile/WC-Co
6-04	6A		-0.0665	0.0057	1	Nitrile/WC-Co
10-04	6B		-0.0991	0.0128	1	Nitrile/WC-Co

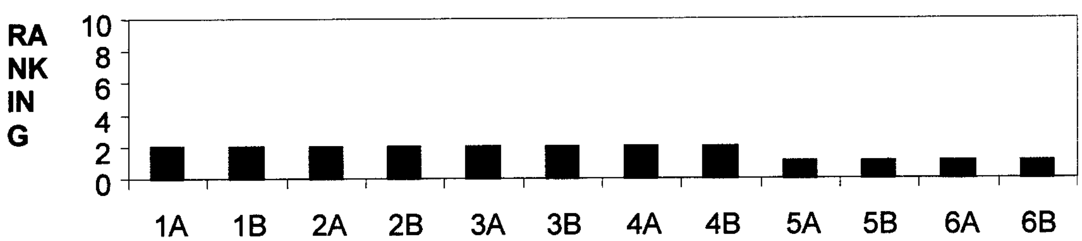


Figure 3-70. Fretting Wear Ranking – Shoe; L12 DOE Matrix (Red against metal bushings; blue against nitrile seals)

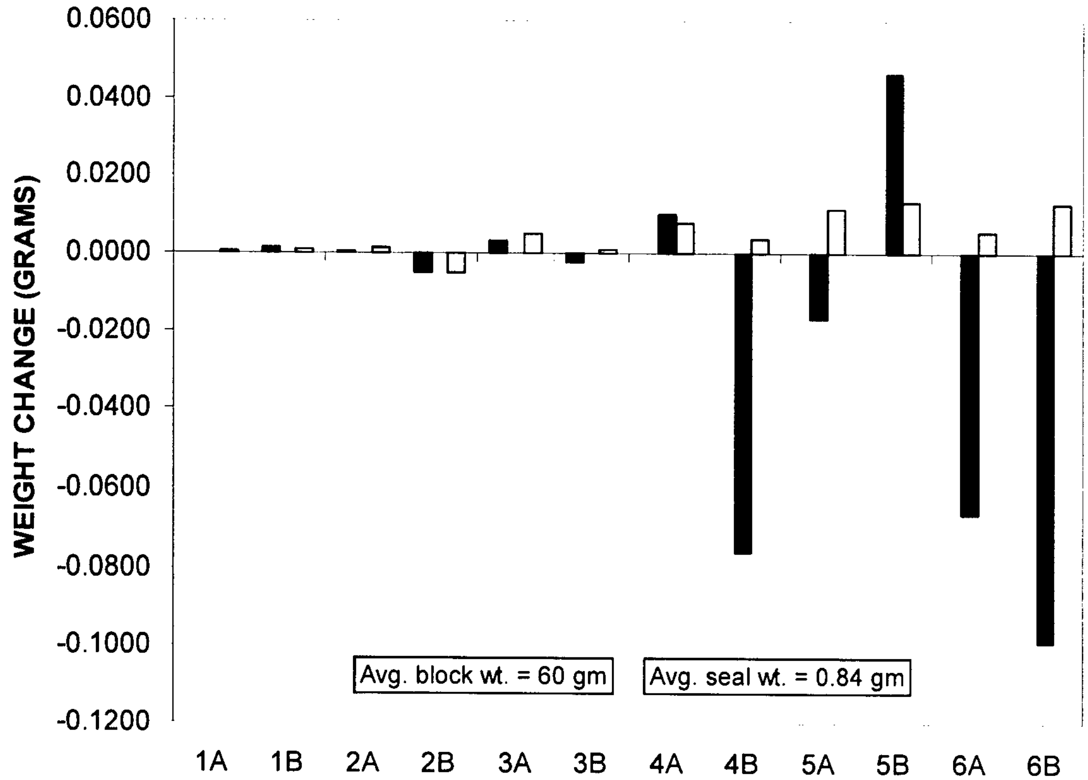


Figure 3-71. Fretting Wear - L12 DOE Matrix; Yellow Data Wear of Coated Shoe; Red Data Wear of Uncoated 4340 Block; Blue Data Wear of Nitrile Seal

The L-12 fretting data showed very little differentiation between materials. This is especially clear from the visual ranking data (Figure 3-70), which showed almost no wear under any conditions.

3.5.6.3. L12 sliding wear tests

The data for sliding wear are shown in . Note that, since this was a DOE matrix, each point corresponds to a different set of conditions, as shown in the matrix of Table 3-47.

Table 3-50. L12 Test Matrix Data - Sliding Wear

TEST NUMBER	TEST SERIES	BUSHING WEIGHT CHANGE	SEAL WEIGHT CHANGE	ROD WEIGHT CHANGE	WEAR RANKING (ROD)
14-04	7A	-0.1271		-0.0200	10
23-04	7B	-0.0633		-0.0003	6
7-04	8A	-0.0218		0.0018	1
17-04	8B	0.0014		0.0049	1
9-04	9A	0.0043		-0.0003	3
19-04	9B	0.0021		0.0069	3
24-04	10A-L		-0.0223		
24-04	10A-R		-0.0383	0.0035	2
29-04	10B-L		-0.0046		
29-04	10B-R		-0.0057	0.0000	2
25-04	11A-L		-0.0049		
25-04	11A-R		-0.0100	0.0107	3
27-04	11B-L		0.0509		
27-04	11B-R		0.0560	0.0102	4
26-04	12A-L		-0.4432		
26-04	12A-R		-0.1761	-0.0040	7
28-04	12B-L		-0.2973		
28-04	12B-R		-0.1348	-0.0184	8

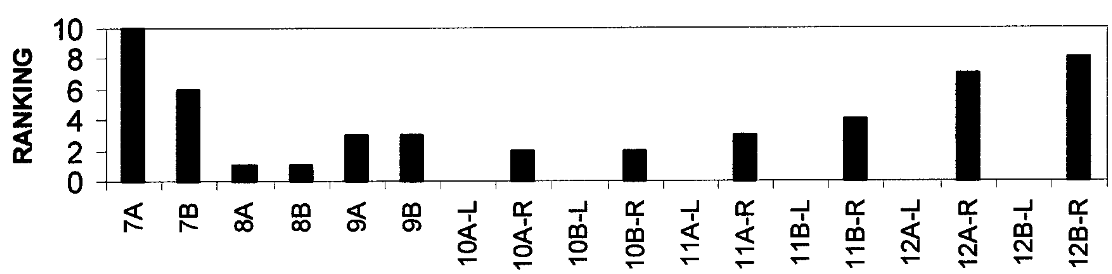


Figure 3-72. Sliding Wear – L12 Data. Visual Wear Ranking – Rod. (Red against bushings; blue against seals)

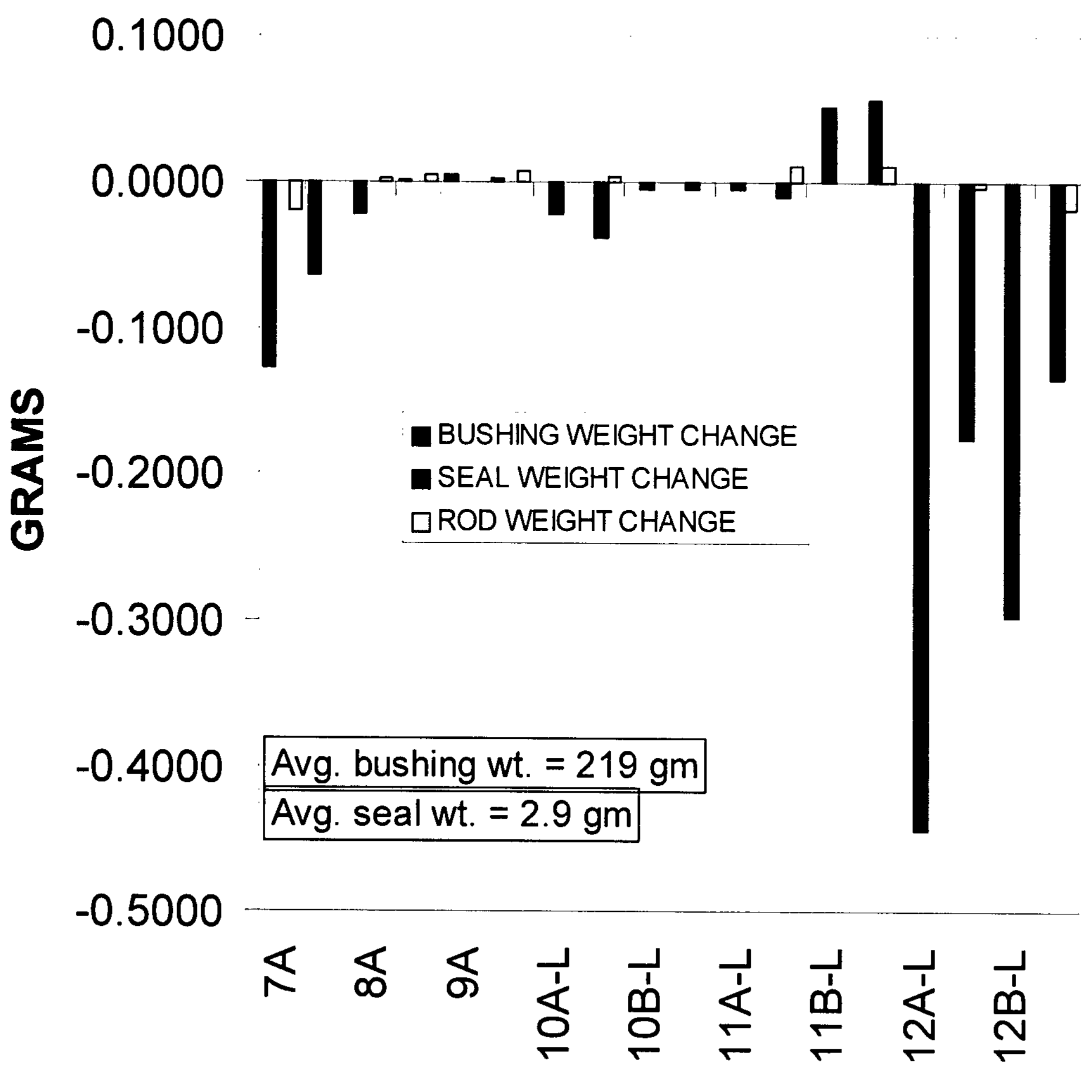


Figure 3-73. Sliding Wear – L12 Data. Weight Change – Bushing/Seal (Yellow data wear of coated rod; red data wear of uncoated bushing; blue data wear of nitrile seal)

From the L12 matrix allowed us to draw the following conclusions for design of the final L8 DOE matrix:

1. Rod coating and bushing type were statistically significant design factors, as expected.
2. Normal load, P_N, was a significant variable using the 72 and 288 lb. values.
3. Test duration (cycles) was a significant variable. For better differentiation, it was decided to use 80,000 and 240,000 cycles as the design values for the L8 matrix.
4. The remaining design factors evaluated in this phase did not provide statistically differentiable performance over the ranges examined. Therefore, each of these became a constant in the L8 matrix, using the following values:
   - ❑ Coating finish – 8 microinches Ra

- ❑ Lubrication – partial (1st hour only, 1 drip/4 min.)
- ❑ Stroke – 1” (total range; i.e., +/-0.5”)
- ❑ Frequency – 1.5 Hz (90 cpm)
- ❑ Temperature – 75°F.

3.5.6.4. L8 sliding wear DOE tests

The L8 test matrix is given in Table 3-48. The wear results are given in Table 3-51 to Table 3-54. The table includes the visual ranking of rod wear as well as weight change for rod, bushing, seal, and liner. Negative weight changes, i.e. weight losses, are in brackets – numbers not in brackets are weight gains.

Figure 3-74 and Figure 3-75 show the wear data for the metal (4340 and AlNiBronze) bushings. Figure 3-76 to Figure 3-78 shows the statistical analysis for this metal bushing wear data. Figure 3-79 to Figure 3-82 show the wear data for bushings, Karon B liners, and nitrile seals from the 3rd and 5th half replicates. Average values are given in Figure 3-83 and Figure 3-84.

Table 3-51. L8 DOE Data - Baseline Metal Bushings

TEST		WEIGHT CHANGE				VISUAL
NO.	ROD/BUSHING/CYCLES/LOAD	ROD	BUSHING	SEAL A	SEAL B	RATING
BASELINE						
49A	49A-EHC/4340/80K/72	0.0041	0.0087			3
49B	49B-EHC/4340/80K/72	(0.0108)	(0.0021)			4
50A	50A-EHC/4340/240K/288	0.0012	(0.0061)			9
50B	50B-EHC/4340/240K/288	(0.0053)	(0.0114)			9
51A	51A-EHC/AlNiBr/80K/288	(0.0032)	(0.0334)			3
51B	51B-EHC/AlNiBr/80K/288	(0.0094)	(0.0107)			3
52A	52A-EHC/AlNiBr/240K/72	0.0035	(0.0181)			3
52B	52B-EHC/AlNiBr/240K/72	(0.0149)	(0.0104)			4
53A	53A-WCCo/4340/80K/288	(0.0115)	(0.0004)			2
53B	53B-WCCo/4340/80K/288	(0.0036)	(0.0168)			5
54A	54A-WCCo/4340/240K/72	(0.0086)	(0.2610)			3
54B	54B-WCCo/4340/240K/72	(0.0045)	(0.0471)			2
55A	55A-WCCo/AlNiBr/80K/72	0.0029	(0.0018)			1
55B	55B-WCCo/AlNiBr/80K/72	(0.0052)	(0.0074)			1
56A	56A-WCCo/AlNiBr/240K/288	0.0019	(0.0675)			8
56B	56B-WCCo/AlNiBr/240K/288	(0.0090)	(0.1493)			9

Table 3-52. L8 DOE Data - 1st and 2nd Half Replicates

NO.	ROD/BUSHING/CYCLES/LOAD	ROD	BUSHING	SEAL A	SEAL B	RATING
1ST L8 HALF-REPLICATE						
57A	57A-WCCoCr/4340/80K/288	(0.0294)	(0.3301)			6
57B	57B-WCCoCr/4340/80K/288	(0.0159)	(0.0068)			2
58A	58A-WCCoCr/4340/240K/72	(0.0196)	0.0018			1
58B	58B-WCCoCr/4340/240K/72	(0.0001)	0.0018			1
59A	59A-WCCoCr/AlNiBr/80K/72	(0.0470)	(0.0059)			2
59B	59B-WCCoCr/AlNiBr/80K/72	(0.0021)	(0.0409)			3
60A	60A-WCCoCr/AlNiBr/240K/288	(0.0292)	(0.1150)			8
60B	60B-WCCoCr/AlNiBr/240K/288	0.0033	(0.0370)			4
2ND L8 HALF-REPLICATE						
61A	61A-EHC/Al/80K/288	(0.0033)	0.0055			9
61B	61B-EHC/Al/80K/288	(0.0095)	(0.0040)			7
62A	62A-EHC/Al/240K/72	0.0003	0.0101			7
62B	62B-EHC/Al/240K/72	(0.0113)	(0.0048)			4
63A	63A-WCCo/Al/80K/72	(0.0077)	0.0078			1
63B	63B-WCCo/Al/80K/72	(0.0017)	(0.0016)			1
64A	64A-WCCo/Al/240K/288	(0.0021)	0.0016			2
64B	64B-WCCo/Al/240K/288	(0.0001)	0.0003			1

Table 3-53. L8 DOE Data - 3rd and 4th Half Replicates

TEST NO.	ROD/BUSHING/CYCLES/LOAD	WEIGHT CHANGE ROD	BUSHING	SEAL A	SEAL B	VISUAL RATING
3RD L8 HALF-REPLICATE						
65A	65A-EHC/NITRILE/80K/288	0.2933	(0.0131)	(0.0751)	(0.0423)	5
65B	65B-EHC/NITRILE/80K/288	(0.0013)	(0.0063)	(0.0366)	(0.0520)	8
66A	66A-EHC/NITRILE/240K/72	(0.0073)	(0.0073)	(0.4355)	(0.2570)	6
66B	66B-EHC/NITRILE/240K/72	(0.0071)	(0.0044)	(0.2583)	(0.2772)	9
67A	67A-WCCo/NITRILE/80K/72	(0.0009)	(0.0124)	(0.0779)	(0.1863)	1
67B	67B-WCCo/NITRILE/80K/72	(0.0035)	(0.0042)	(0.0058)	(0.0078)	2
68A	68A-WCCo/NITRILE/240K/288	0.0026	(0.0101)	(0.0288)	(0.0373)	1
68B	68B-WCCo/NITRILE/240K/288	0.0013	(0.0016)	(0.0226)	(0.0335)	2
4TH L8 HALF-REPLICATE						
69A	69A-EHC/KARON/80K/288	0.0005	(0.0008)			1
69B	69B-EHC/KARON/80K/288	0.0003	0.0622			1
70A	70A-EHC/KARON/240K/72	(0.0006)	(0.0010)			3
70B	70B-EHC/KARON/240K/72	(0.0016)	0.0776			2
71A	71A-WCCo/KARON/80K/72	0.0002	0.0003			1
71B	71B-WCCo/KARON/80K/72	(0.0008)	0.0055			1
72A	72A-WCCo/KARON/240K/288	(0.0071)	(0.0098)			1
72B	72B-WCCo/KARON/240K/288	0.0021	0.0541			1

Table 3-54. L8 DOE Data - 5th and 6th Half Replicates

TEST NO.	ROD/BUSHING/CYCLES/LOAD	WEIGHT CHANGE ROD	BUSHING	SEAL A	SEAL B	VISUAL RATING
5TH L8 HALF-REPLICATE						
73A	73A-EHC/KARON/80K/72	0.0103	0.0035			2
73B	73B-EHC/KARON/80K/72	0.0004	0.0091			2
74A	74A-EHC/KARON/240K/288	(0.0017)	0.0034			1
74B	74B-EHC/KARON/240K/288	(0.0008)	0.0102			1
75A	75A-WCCoCr/KARON/80K/288	(0.0335)	0.0022			1
75B	75B-WCCoCr/KARON/80K/288	(0.0011)	0.0077			1
76A	76A-WCCoCr/KARON/240K/72	(0.0320)	0.0056			1
76B	76B-WCCoCr/KARON/240K/72	(0.0320)	0.0101			1
77A	77A-EHC/AlNiBr/80K/288	(0.0016)	(0.0328)			9
77B	77B-EHC/AlNiBr/80K/288	0.0022	(0.0235)			6
78A	78A-EHC/AlNiBr/240K/72	(0.0065)	(0.0463)			8
78B	78B-EHC/AlNiBr/240K/72	0.0005	(0.0590)			7
6TH L8 HALF-REPLICATE						
79A	79A-EHC/NITRILE/80K/72	(0.0016)	(0.0018)	(0.0604)	(0.0783)	8
79B	79B-EHC/NITRILE/80K/72	(0.0007)	0.0030	(0.0072)	(0.0012)	7
80A	80A-EHC/NITRILE/240K/288	(0.0021)	(0.0040)	(0.1539)	(0.1256)	8
80B	80B-EHC/NITRILE/240K/288	(0.0166)	(0.0229)	(0.0373)	(0.0394)	8
81A	81A-WCCoCr/NITRILE/80K/288	(0.0049)	(0.0391)	(0.1289)	(0.2392)	2
81B	81B-WCCoCr/NITRILE/80K/288	(0.0212)	(0.0407)	(0.0316)	(0.0308)	2
82A	82A-WCCoCr/NITRILE/240K/72	0.0023	0.0006	(0.0926)	(0.2962)	2
82B	82B-WCCoCr/NITRILE/240K/72	(0.0113)	(0.0047)	(0.0139)	(0.0479)	1

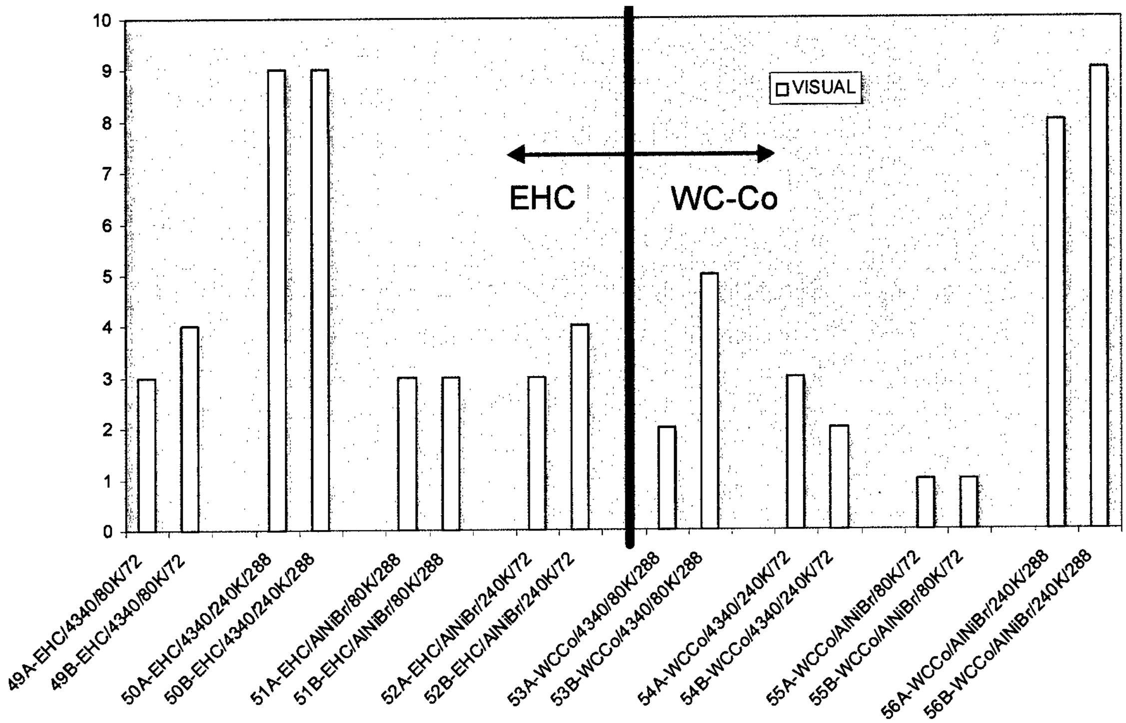


Figure 3-74. Sliding Wear, L8 DOE – Visual Rankings for Baseline Metal Bushings

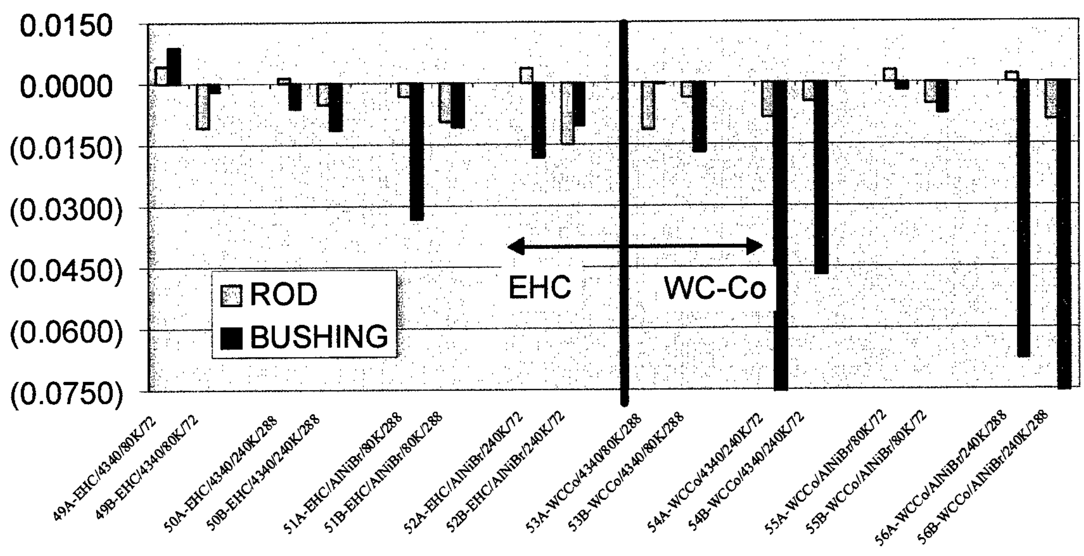
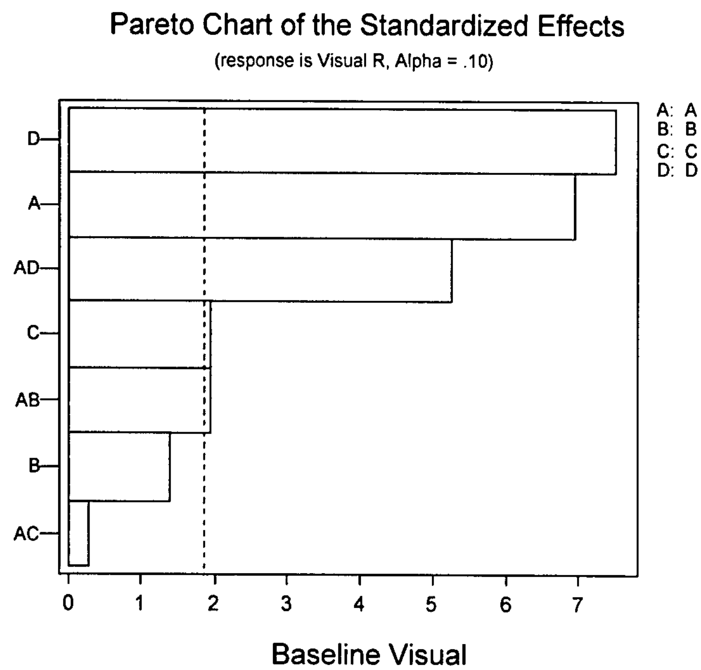


Figure 3-75. Sliding Wear, L8 DOE – Weight Loss for Baseline Metal Bushings



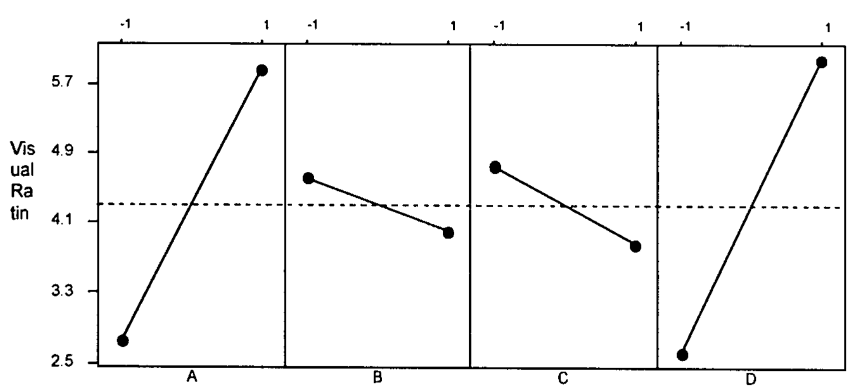


Figure 3-76. Pareto Chart and Visualization of the Major Effects in the L8 DOE Based on Visual Wear Rating; Only Effects D and A (normal load and number of cyles) are Statistically Significant

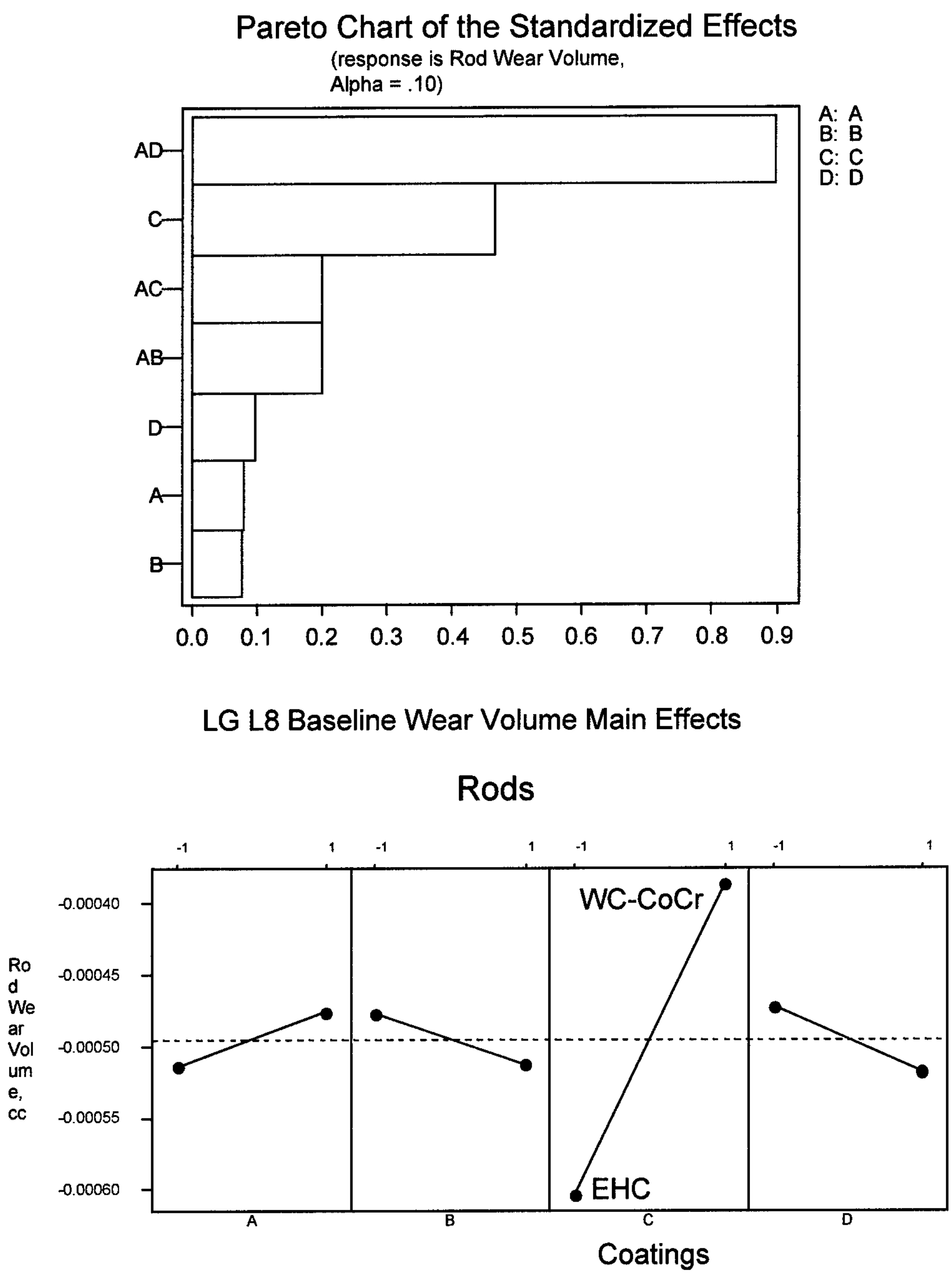
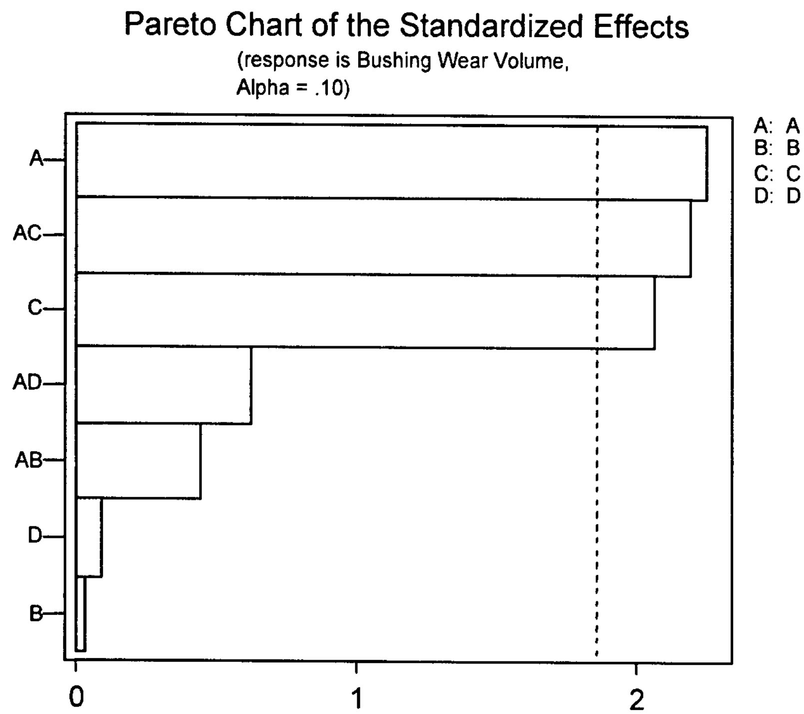


Figure 3-77. Pareto Chart and Visualization of the Major Effects in the L8 DOE Based on Rod Wear Volume; Only Effect C (coating material) is Statistically Significant



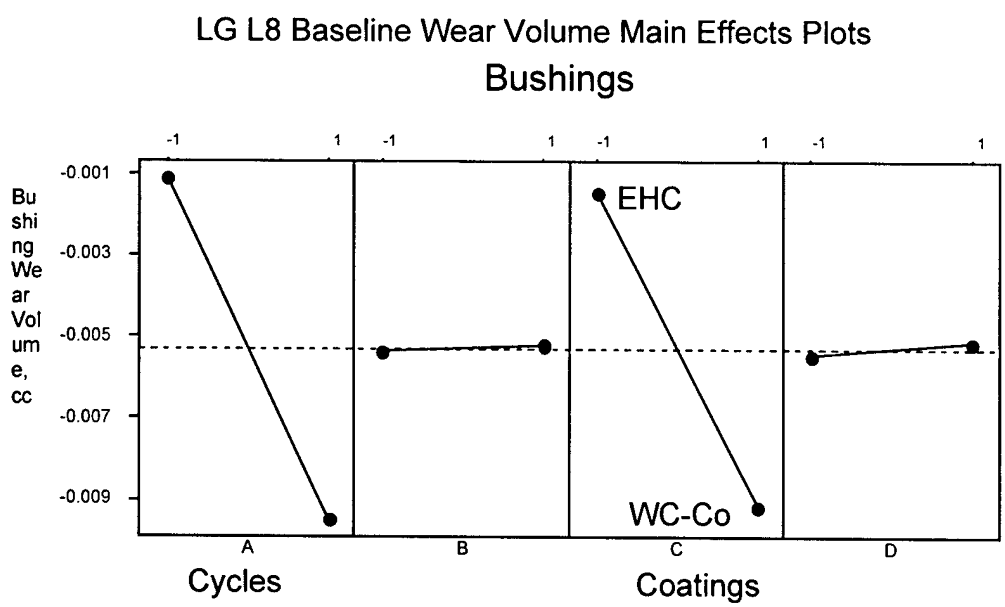


Figure 3-78. Pareto Chart and Visualization of the Major Effects in the L8 DOE Based on Bushing Wear Volume; Only Effects A and C (number of cycles and coating material) are Statistically Significant

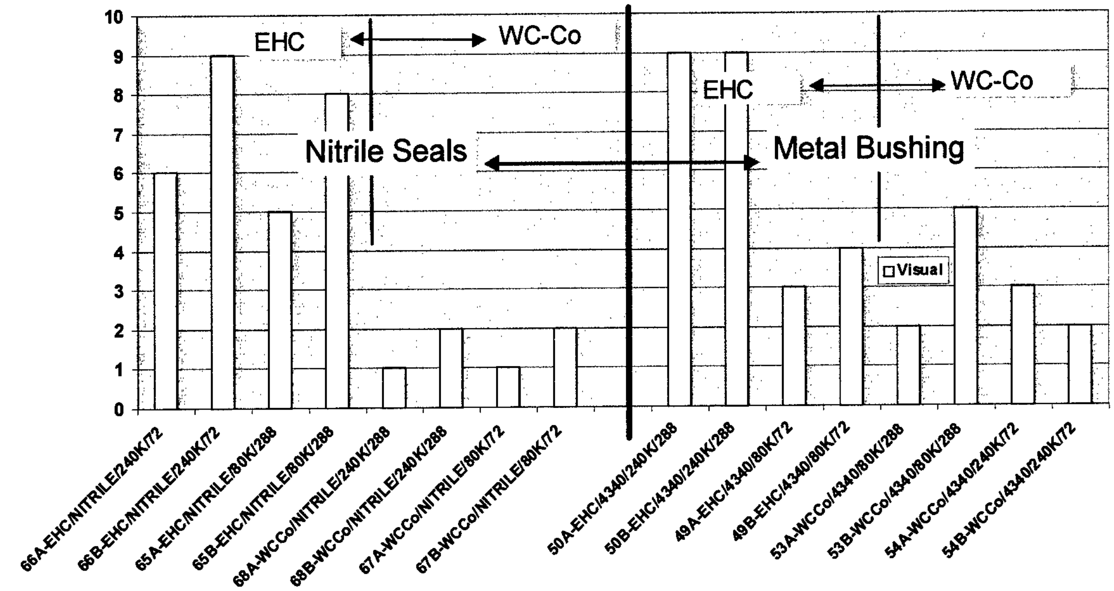


Figure 3-79. L8 DOE Data for 3rd Half Replicate – Visual Ranking for Rod Wear (shows EHC and WC-Co on metal bushings and nitrile seals)

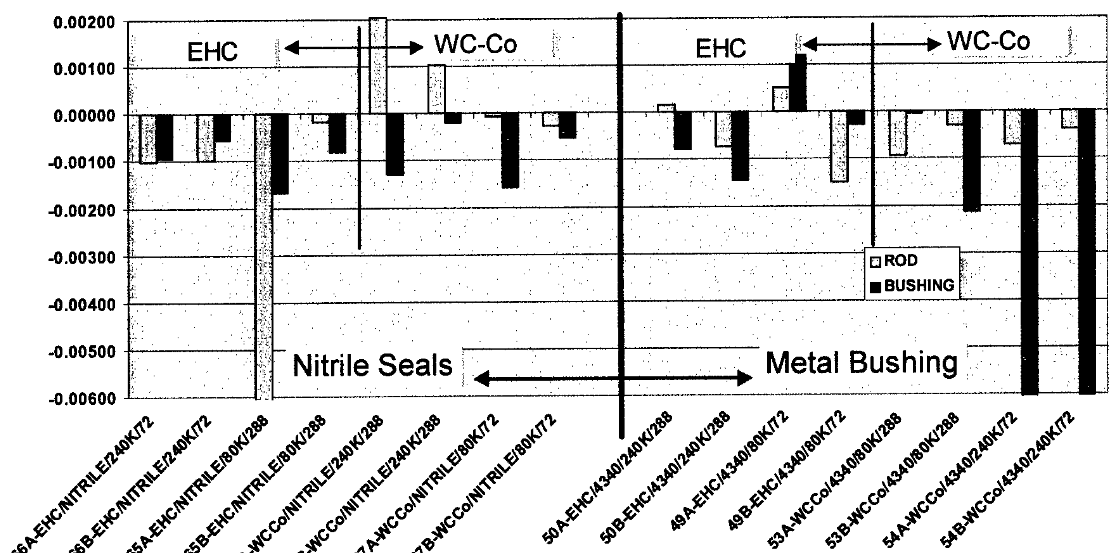


Figure 3-80. L8 DOE Data for 3rd Half Replicate – Weight Loss (shows EHC and WC-Co on metal bushings and nitrile seals)

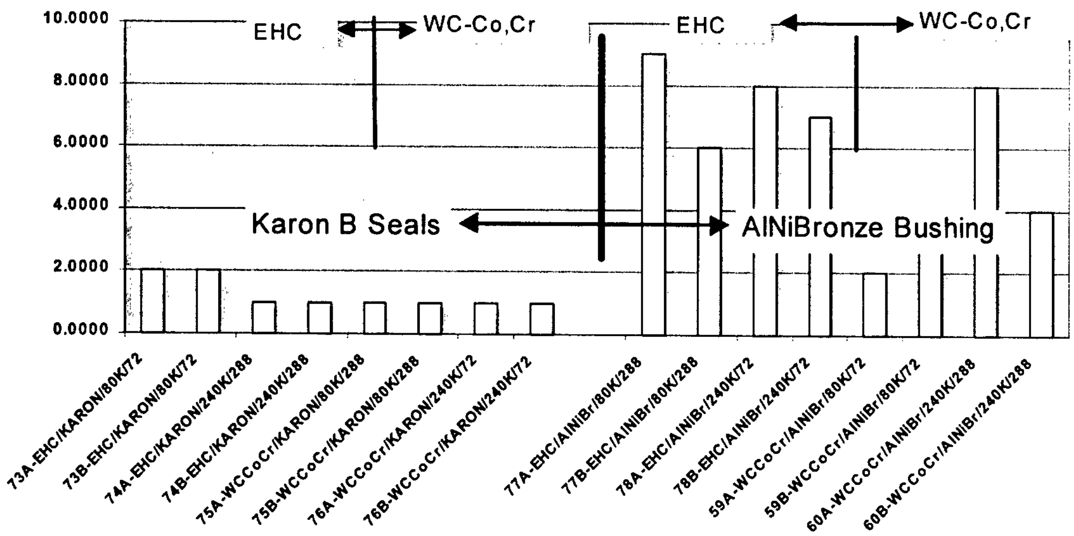


Figure 3-81. L8 DOE Data for 5th Half Replicate – Visual Ranking for Rod Wear (shows EHC and WC-Co on AlNiBronze bushings and Karon B liners)

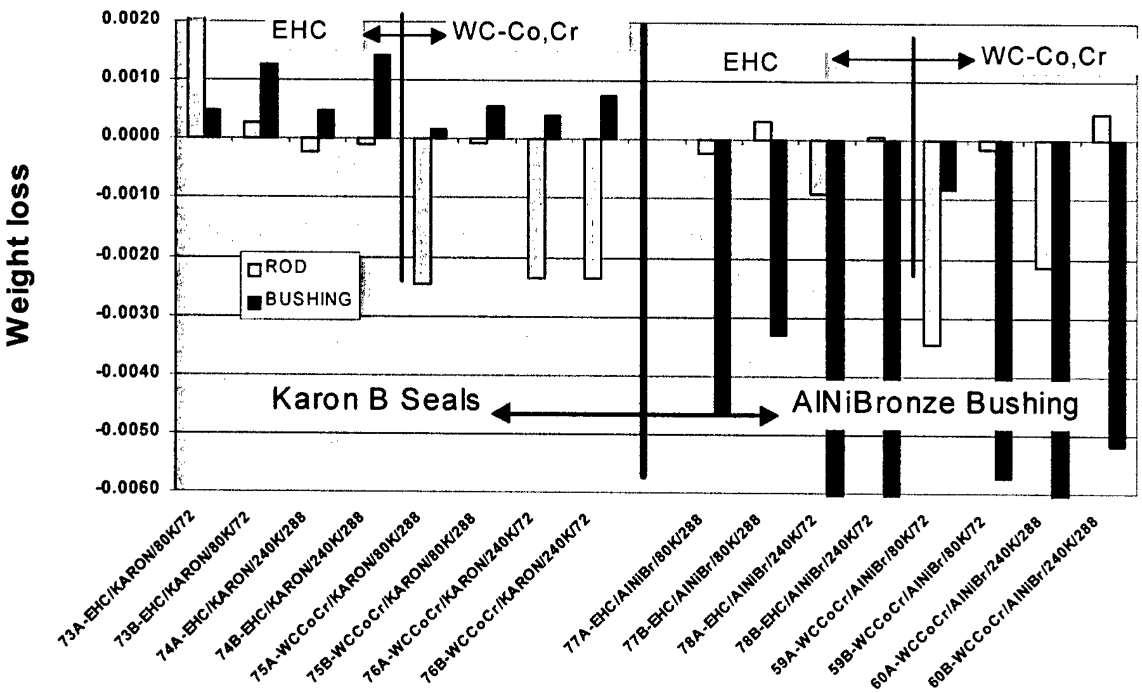


Figure 3-82. L8 DOE Data for 5th Half Replicate – Weight Loss (shows EHC and WC-Co on AlNiBronze bushings and Karon B liners)

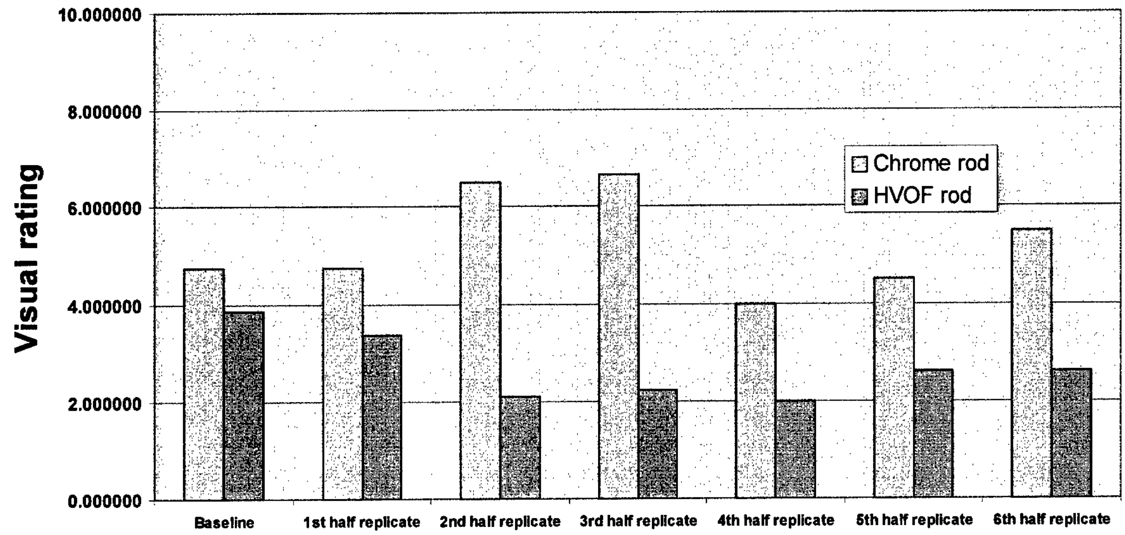


Figure 3-83. Average Rod Wear for L8 Matrix - Visual Rating

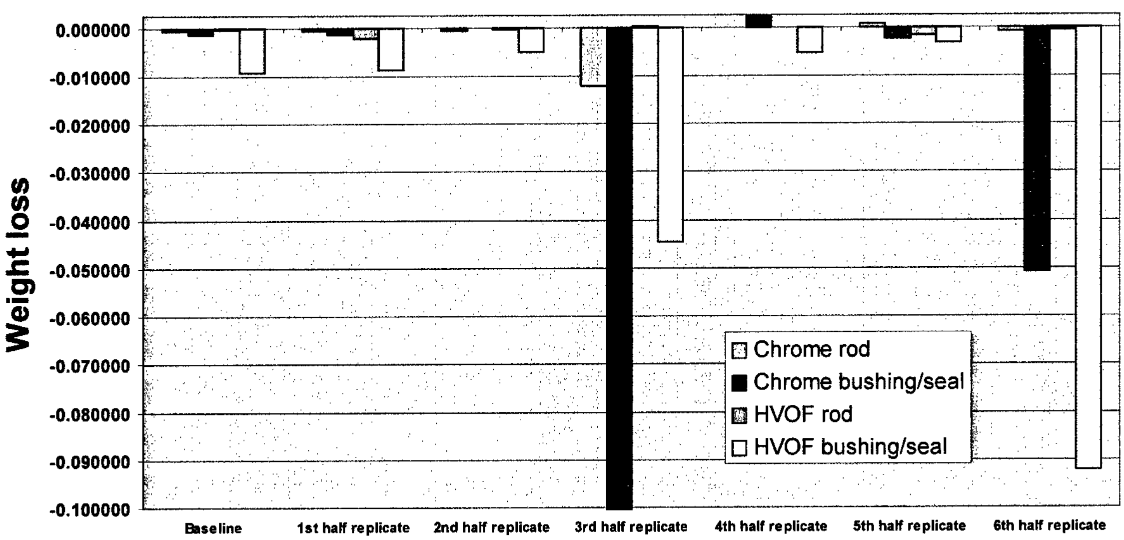


Figure 3-84. Average Rod and Bushing/Seal Wear for L8 Matrix - Weight Loss

3.5.7. Discussion of wear results

3.5.7.1. Fretting

Fretting tests showed very little wear. The HVOF coatings showed almost no wear against the nitrile seals, but seal wear was very unstable. We conclude that fretting is not a good test of wear, making fretting tests poor discriminators between the performance of EHC and HVOF coatings.

3.5.7.2. Sliding wear

At this point only the baseline wear against metal bushings has been statistically

analyzed. The analysis leads to the following conclusions:

- As we would expect, wear is strongly influenced by load and number of cycles (Figure 3-76).
- As we have found in most rig and flight tests, WC-CoCr shows significantly less wear than EHC (Figure 3-77)
- Also as we have found in rig and flight tests, WC-Co tends to wear the bushings more that EHC does (Figure 3-78).
- Most factors were not statistically significant in discriminating between EHC and HVOF coatings in wear testing. Statistically insignificant factors were surface finish, lubrication, stroke, frequency, and temperature. This does not mean that these factors were not significant in wear, but that they did not discriminate between the performance of the different coatings. The only real surprise here is that surface finish did not discriminate, whereas in flight testing and rig testing, surface finish has been found to strongly affect seal wear and seal life, with smooth HVOF coatings giving much better performance than rough coatings[1,2].

Once the detailed statistical analysis is complete it will be possible to analyze the data more thoroughly. However, some observations can be made at this time:

- In general, the two tests at each condition were reasonably consistent, especially in visual ranking. Weight change was usually large for both measurements or small for both (although small changes were often of opposite sign). This is not unexpected since the typical weight change was less than 0.01 grams in 880 grams, or 0.001%, and small amounts of trapped oil and debris easily exceeded the true weight change.
- Overall, rod wear tended to be less for HVOF coatings than for EHC, but bushing or seal wear tended to be higher. This is consistent with the detailed analysis above for bushings. The difference between EHC and HVOF coatings was especially clear for nitrile seals (Figure 3-83). There was no evident difference between WC-Co and WC-CoCr.
- The visual ratings for rods run against Al-Ni bronze bushings tended to be higher (worse) because of metal transfer from the bushing to the rod surface.
- Visual wear rankings were the lowest (best) for the Karon B liners. In most cases, the rod surfaces were nearly pristine after being tested against these liners. Weight loss measurements were not nearly as clear.

3.5.8. Significance

These wear tests generally bear out the findings of rig and flight tests. HVOF WC-Co and WC-CoCr both experience less wear than EHC. However, they tend to cause more wear in adjacent seals and bushings. In order to counteract this tendency users have successfully used two approaches – superfinishing the HVOF coating, and wear-coating the adjacent parts [3.4].

3.5.9. Conclusion

Fretting tests are not useful for these types of wear situations, but sliding wear tests can discriminate between the different coatings and seal materials. Overall, HVOF coatings show less wear than EHC, but tend to cause more wear on adjacent components. **Passes acceptance criteria**

3.6. Impact data

3.6.1. Data summary

Table 3-55. Quick Data Locator (Click on item number to view)

Item	Item number
Gravelometer test matrix and rankings (visual, touch, Ra)	Table 3-58
Gravelometer surface condition after testing	Figure 3-87, Figure 3-88, Figure 3-89
Circumferential cracking around the ball impact zone	Figure 3-91
Radial cracking around the ball impact zone	Figure 3-92

3.6.2. Rationale

Areas coated with HVOF in place of chrome will often be exposed to potential damage from runway debris and larger items such as dropped tools. Impact testing was therefore divided into

- high-velocity small particle impact simulating runway debris (evaluated by Gravelometry), and
- low velocity large item impact simulating dropped tools, etc. (evaluated by Dropped Ball Impact testing).

3.6.3. Specimen fabrication

All specimens were fabricated from 4340 round bar

- 1" diameter, 6" long
- Tensile strength and heat treat – 260-280 ksi per MIL-H-6875
- Shot peen – 8-10A, S230, wrought steel shot, per AMS 2432, computer controlled, 100% coverage, except a 0.75" section at one end of the rod
- Grit blast prior to coating – Specimens were gripped on the non-peened area and a 5" section grit blasted:
    - For EHC with 180-220 grit alumina or glass beads
    - For HVOF coating with 54 grit alumina at 60 psi at 90° angle of impingement, per MIL-STD-1504.
- Coating – per methodology in Section 3.6.4 below
    - Thickness – final thickness 0.003" and 0.010" (see Table 3-56). Coatings

were deposited 0.002-0.003” thicker to allow for final grinding.

- Embrittlement relief heat treat - 375°F for EHC plated samples only.
- Grind after coating
  - For EHC low stress grind to 16μ” finish per MIL-STD-866
  - For HVOF low stress grind to 8μ” finish per BAC 5855

3.6.4. Coating deposition methodology

Specimens were coated , and where necessary embrittlement heat treated, by Southwest Aeroservice. Coatings were deposited under the SWA Boeing-approved specifications for EHC, WC-Co, and WC-CoCr. Coating materials and thicknesses tested are summarized in Table 3-56.

Table 3-56. Hydrogen Embrittlement Coating Thicknesses (ground)

Coating	Low thickness	High thickness
EHC	0.003”	0.010”
WC-Co	0.003”	0.010”
WC-CoCr	0.003”	0.010”

Samples were coated at Southwest Aeroservice (Tulsa, OK). Coating conditions were Southwest Aeroservice proprietary specifications, as follows:

- Hard chrome – QQ-C-320B
- WC-Co – DiamondJet gun.
  - SWA Control Specification UHP 520.1, technique SWATS 141
  - Powder – Amperit 526.062/895
  - Fuel – Hydrogen
- WC-CoCr – DiamondJet gun
  - SWA Control Specification UHP 545, technique SWATS 140
  - Powder – Sulzer Metco 5847
  - Fuel – Hydrogen

3.6.5. Test methodology

3.6.5.1.Gravelometry

Specification: ASTM D 3170, “Standard Test Method for Chipping Resistance of Coatings”

Modifications: The standard test calls for flat panels and gravel sized between 9.5 and 16 mm. 1” dia round rods were used to more closely approximate landing gear parts, and a non-standard gravel size was used.

Significance: For use on landing gear, coatings must be able to withstand debris impact on landing and takeoff, when the coated sections may be

fully exposed.

Sample types: 1" round rod (traditional flat samples were coated by Boeing and used for comparison.)

Sample materials: 4340

Sample heat treat: 260-280 ksi UTS

Coatings: EHC, WC-Co, WC-CoCr, 0.003" and 0.010", ground to 16μ" for EHC and to 8μ" Ra for HVOF.

Test equipment: Gravelometer (see Figure 3-85). This equipment feeds a stream of gravel into an air jet, striking the sample at a defined angle. Impact on a round rod is normal incidence to grazing incidence since the gravel stream covers the entire diameter.

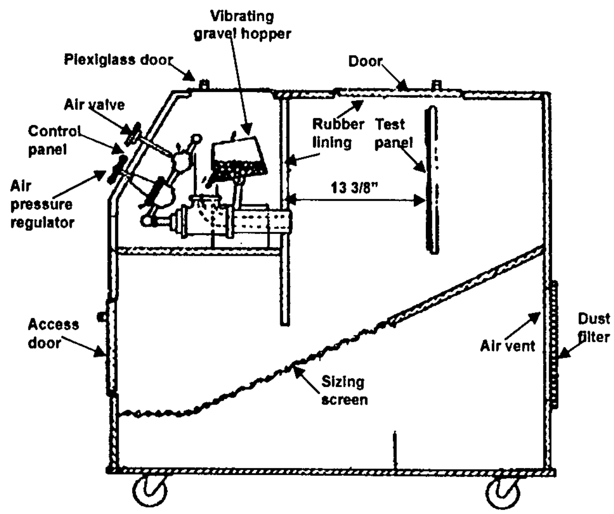


Figure 3-85. Gravelometry Chamber (Boeing)

Test description:

Tests were carried out at Boeing Seattle, using a non-standard gravel and a standard air pressure of 70 psi (approximately 200 mph air-jet speed).

1" diameter round bars were used. The round bars were coated by Southwest Aeroservice using their Boeing-approved specifications for EHC, WC-Co, and WC-CoCr. Flat specimens coated independently for Boeing were included for comparison with prior Boeing work.

Coatings and thicknesses tested are summarized in Table 3-57.

After testing the surfaces were examined for damage and roughening as follows:

- microscopically (visual ranking)
- touch (finger nail)
- R_a measurement by profilometry

The JTP required only visual ranking of coated round rods. However, the additional ranking methods were added by Boeing for better comparison with prior experience.

3.6.5.2.Dropped ball impact

Specification: No existing standard. Followed method similar to that used by NAWCAD for similar evaluations.

Modifications: NAWCAD method modified to evaluate impact within coated area

(rather than on edge).

Significance: For use on landing gear, coatings must be able to withstand FOD by impact from large pieces of debris, dropped tools, etc.

Sample types: 1" round rod

Sample materials: 4340

Sample heat treat: 260-280 ksi UTS

Coatings: EHC, WC-Co, WC-CoCr, 0.003" and 0.010", ground to 16μ" for EHC and to 8μ" Ra for HVOF.

Test equipment: Impact system comprising guidance tube and 52100 steel ball, diameter 1 7/8", weight 0.97 lb (see Figure 3-86).

Table 3-57. Gravelometry and Ball Impact Coating Thicknesses (ground)

Coating	Low thickness	High thickness
EHC	0.003-0.004"	0.010-0.011"
WC-Co	0.003-0.004"	0.010-0.011"
WC-CoCr	0.003-0.004"	0.010-0.011"

Test description:

Tests were carried out at Dayton T. Brown using the apparatus of Figure 3-86. A 0.97 lb ball bearing was dropped down a plastic tube (to ensure correct aim) to strike the rod radially. When the ball rebounded a stop was quickly inserted between the sample and the tube to limit each drop to a single impact. The ball was checked after each drop to ensure that it had not suffered any obvious damage or flattening.

The damage zone was observed as a function of impact height. Single-impact tests were evaluated microscopically to determine the extent of cracking. Multiple impact tests (up to 50 impacts at a single point) were also made.

The coatings and thicknesses tested are summarized in Table 3-57. Drop heights were 24", 60", 72", 93", and 102".

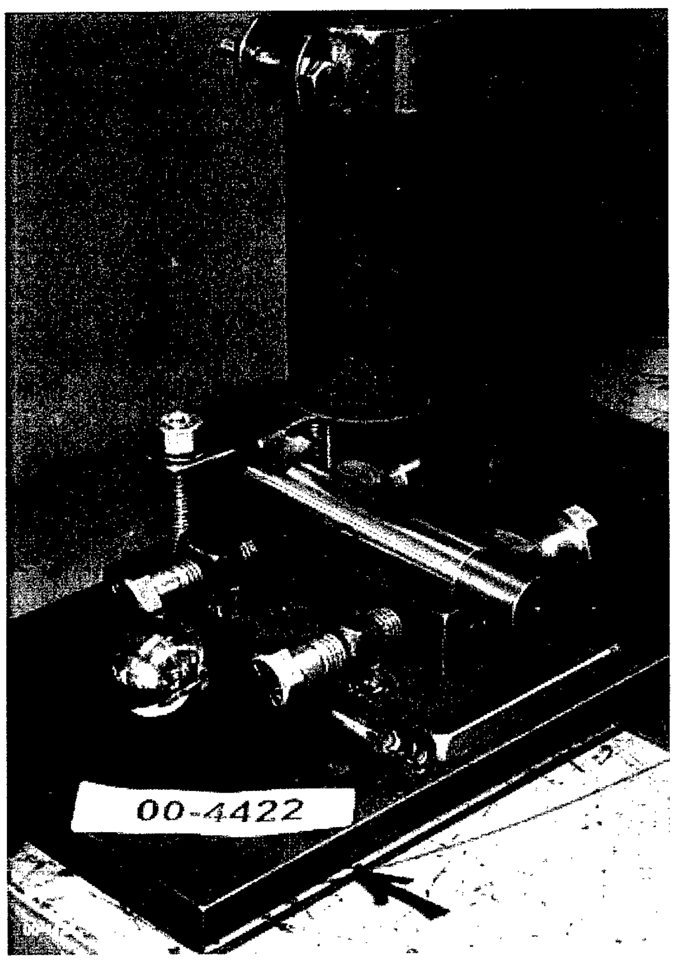


Figure 3-86. Close-up of Ball Impact Equipment, Showing Ball Delivery Tube and Sample in Vise

3.6.6. Test results

3.6.6.1. Gravelometry

Table 3-58 summarizes the evaluations made by Boeing.

Table 3-58. Summary of Gravelometry Test Observations (Rankings from 1 (best) to 3 (worst) for different evaluation methods)

Evaluation method	0.003-0.004"			0.010-0.011"		
	EHC	WC-Co	WC-CoCr	EHC	WC-Co	WC-CoCr
Visual	3	1	2	3	1	2
Touch	1	2	3	3	2	3
Ra*	1	1	2	1	1	2

* Note: Boeing regards the profilometer readings as very questionable

To supplement the observations in Table 3-58, micrographs were taken of selected sample surfaces. These are shown in Figure 3-87 to Figure 3-89.

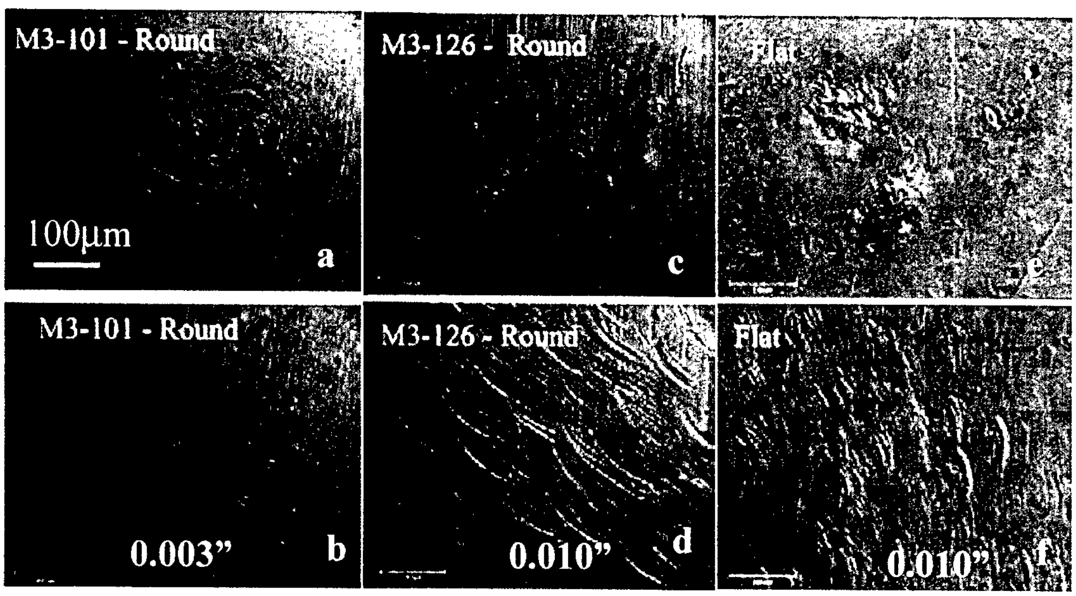


Figure 3-87. Surfaces of EHC Coatings after Gravelometry Testing; a) and b) 0.003"-thick EHC on Rods; c) and d) 0.010"-thick on Rods; e) and f) 0.010"-thick on Flats

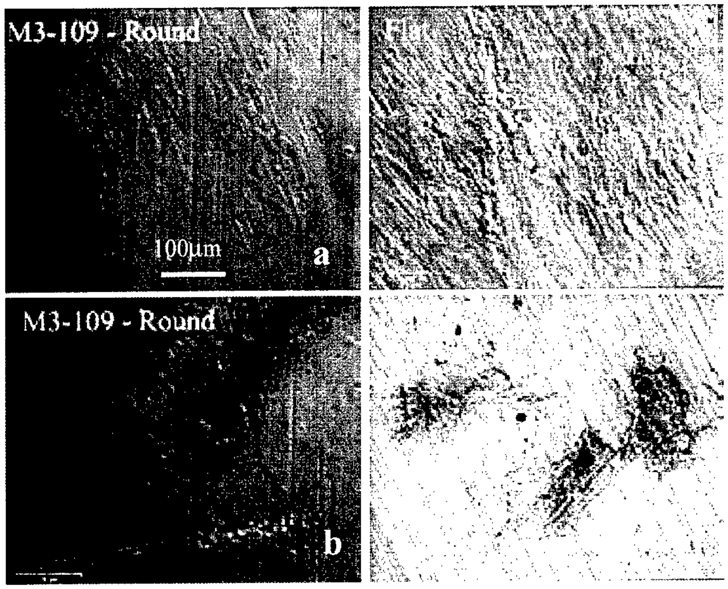


Figure 3-88. Surfaces of WC-Co Coatings after Gravelometry Testing; a) and b) 0.003"-thick on Rods; c) and d) 0.003"-thick on Flats

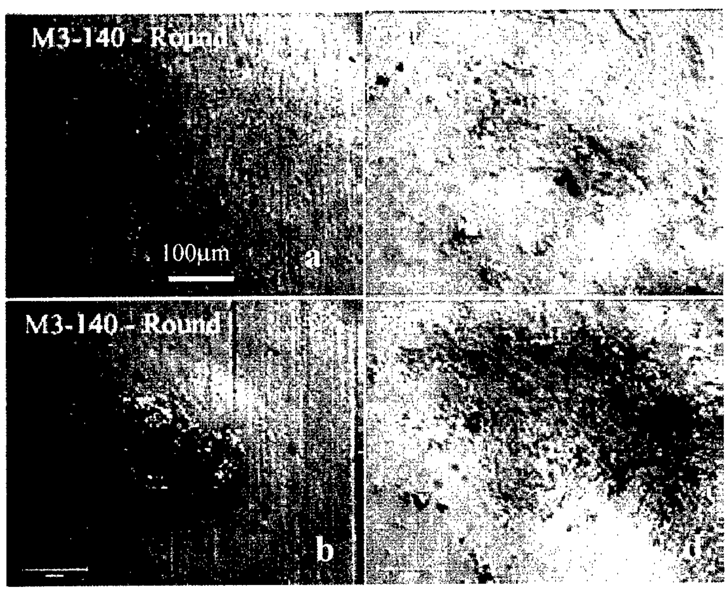


Figure 3-89. Surfaces of WC-CoCr Coatings After Gravelometry Testing; a) and b) 0.003"-thick on Rods; c) and d) 0.010"-thick on flats

3.6.6.2. Dropped ball impact

See Appendix 5 of the JTR [3.1] for raw impact data and micrographs.

For all impacts, including up to 50 drops from 72" onto a single point, there was **no visible sign of cracking or coating damage on any sample**. The only observable damage was an approximately 5mm x 2.5mm flattened area. Microscopic observation showed this area to be bounded by circumferential cracks of varying visibility, shown arrowed in Figure 3-90, and often some radial cracking along the bar axis (3 o'clock and 9 o'clock locations in the figure).

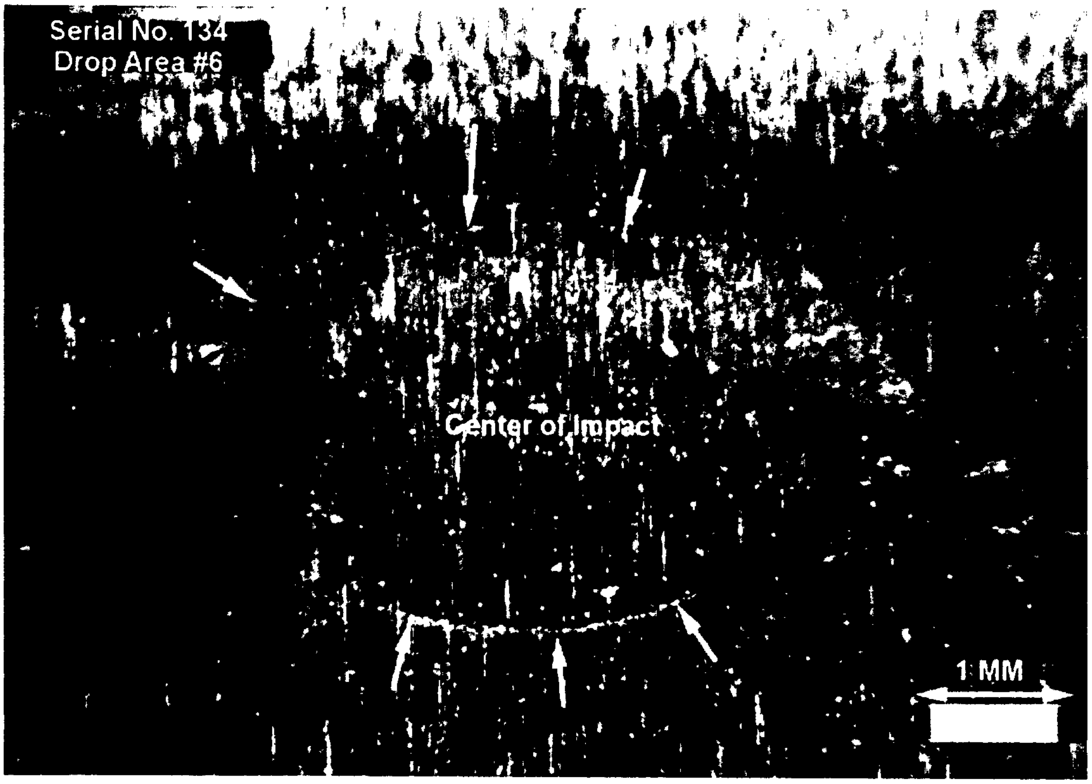


Figure 3-90. Impact Area on 0.010"-thick WC-CoCr , 72" Drop Height – Grazing Incidence Light (Bar axis is horizontal)

In order to make a comparative assessment, 100X micrographs were made of the 24", 60", and 102" drop impact zones. The micrographs were taken at the 12 or 6 o'clock position on Figure 3-90 (whichever gave the clearest photograph) and similarly at the 3 or 9 o'clock position. The number of large and fine circumferential cracks visible in the micrographs around the impact were counted separately, as well as the number of radial cracks at the 3 and 9 o'clock positions (i.e. parallel to the rod axis). (There were no radial cracks at the 12 and 6 o'clock positions on any sample.)

Figure 3-91 shows the total number of circumferential cracks, and Figure 3-92 the total number of radial cracks.

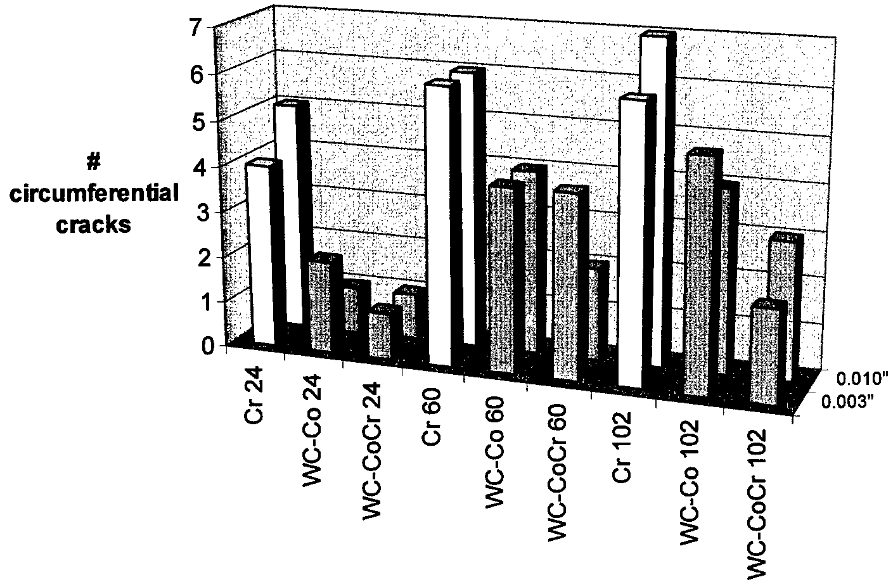


Figure 3-91. Circumferential Cracking Around Impact Point for 0.003"- and 0.010"-thick Coatings at Different Ball Drop Heights

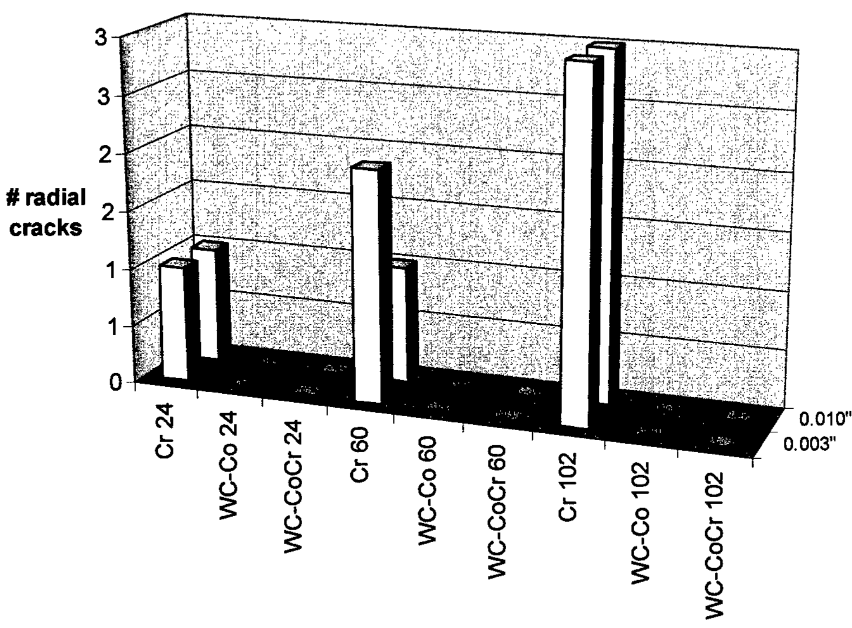


Figure 3-92. Radial Cracking Along Rod Axis for 0.003"- and 0.010"-thick Coatings at Different Ball Drop Heights

3.6.7. Discussion of impact results

In both types of impact tests, results are determined by visual inspection. Consequently they are primarily qualitative and can only show quite significant differences.

3.6.7.1.Gravelometry

The results of Table 3-58 are based on the full tested area of the rods and flats, while the micrographs of Figure 3-87 to Figure 3-89 represent selected areas, chosen to illustrate different types of surface damage. Clearly, both coating materials can be damaged by gravel impact, but there is no obvious major difference between the types or extent of damage. Boeing's overall conclusion, as shown in Table 3-58, is that HVOF coatings are a little better than chrome using the visual comparison specified in the JTP, and about equal using the touch and Ra rankings.

3.6.7.2.Dropped ball impact

Note: Because the reflectivity of the chrome was higher than that of the HVOF coatings, cracking was easier to see in the chrome, which could slant the data to some degree, since it is easier to see thin cracks in chrome than in HVOF coatings. However, the difference is not substantive enough to prevent observation of most cracks and invalidate the results.

From Figure 3-91 and Figure 3-92 we conclude the following:

- Cracking is clearly more extensive in hard chrome than in the HVOF coatings.
- The number of cracks increases with drop height (i.e. with impact velocity or energy). The increase was more significant in chrome than in HVOF.
- Chrome shows some radial cracking along the rod axis and the amount of cracking increases somewhat with drop height. HVOF coatings show no radial cracking,.
- There is no evident dependence of damage on coating thickness.
- WC-CoCr may show somewhat less cracking than WC-Co, but if so the difference is marginal.

3.6.8. Significance

While gravel impact performance is very similar, HVOF coatings are likely to be less sensitive than chrome to FOD by dropped tools or debris thrown up from the runway. This is likely to lessen the frequency of I-level repair due this type of problem. However, the need for repair is largely dictated by post-damage performance (such as corrosion, spalling, etc.) rather than by the initial damage itself. These tests provide no information on this issue, and because of the variability of field conditions this aspect of performance is likely only to be learned in the field.

3.6.9. Conclusion

Ball impact performance of both WC-Co and WC-CoCr is better than chrome, while gravel impact is equal to or better than chrome. **Passes acceptance criteria.**

3.7. Hydrogen embrittlement data

3.7.1. Data summary

Table 3-59. Quick Data Locator (Click on item number to view)

Item	Item number
Test matrix	Table 3-61
Average time to failure – data summary	Table 3-65
Sequence 1 average time to failure (process embrittlement)	Figure 3-98
Sequence 2 average time to failure (diffusion of H through HVOF)	Figure 3-99
Sequence 3 average time to failure (environmental embrittlement, unscribed)	Figure 3-100
Sequence 3 average time to failure (environmental embrittlement, scribed)	Figure 3-101
Sequence 3 – comparison notched and un-notched, DI water	Figure 3-103
Sequence 3 – comparison notched and un-notched, 5% NaCl	Figure 3-104

3.7.2. Rationale

In common with most other aqueous plating methods, the chrome plating process generates hydrogen at the surface being plated. This hydrogen can be absorbed into high strength steels, where it concentrates in high-stress regions and causes hydrogen embrittlement (HE). Under static stress cracks can initiate and grow rapidly in this embrittled steel, causing catastrophic failure. For this reason most electroplating specifications for high strength steels require a hydrogen bakeout (typically 375°F for up to 23 hours, depending on the type and strength of the steel) to remove the absorbed hydrogen.

Corrosive liquids can breach chrome plate and HVOF coatings by penetrating through cracks and defects, causing substrate corrosion. This can happen during processing steps subsequent to chrome plating or HVOF coating, during service, or even during later overhaul cycles. The hydrogen produced during the corrosion process can also cause hydrogen embrittlement and failure under static load. In high strength steels, this is termed "environmental hydrogen embrittlement" and is commonly associated with the more general term "stress corrosion cracking".

The purpose of embrittlement testing in the JTP was to determine the relative effects of

HVOF and EHC coatings on the susceptibility of 4340 steel to HE, in three test sequences:

Sequence 1. To determine if the HVOF process causes hydrogen embrittlement. (Mechanical tests run at Metcut.)

Sequence 2. To dermine if hydrogen can permeate through HVOF coatings, permitting areas adjacent to the HVOF coating to be electroplated and baked out by hydrogen diffusion through the HVOF. Since this Sequence was designed only to test hydrogen diffusion through HVOF coatings, there was no chrome baseline. (Mechanical tests run at Metcut.)

Sequence 3. To determine whether HVOF-coated steel is more or less sensitive to environmental hydrogen embrittlement than chrome plated steel. (Tests run at Boeing.)

As with all other JTP testing, the baseline was EHC.

3.7.3. Specimen fabrication

Specimens were standard ASTM F519, Type 1a.2 notched bars fabricated from 4340 steel by Smith-Williston of Seattle. The notch tensile strength of the bars was measured at 373 ksi. A typical specimen is shown in Figure 3-93.

Figure 3-93. F-519, Type 1a.2 Specimen Coated with 0.010"-thick WC-Co

In accordance with ASTM F-519, the uncoated specimen had a diameter of 0.333", with a notch 0.049" deep and a notch tip radius of 0.010".

3.7.4. Coating deposition methodology

Specimens were coated, and ground or given a hydrogen bakeout where necessary (see Table 3-61), by Southwest Aeroservice. Coatings were processed in accordance with Boeing-approved specifications for EHC, WC-Co, and WC-CoCr. Coating materials and thicknesses tested are summarized in Table 3-60.

Table 3-60. Hydrogen Embrittlement Coating Thicknesses (ground)

Coating	Low thickness	High thickness
EHC	0.003"	0.010"
WC-Co	0.003"	0.010"
WC-CoCr	0.003"	0.010"

Southwest Aeroservice coating conditions were, as follows:

- Hard chrome – QQ-C-320B
- WC-Co – DiamondJet gun.
    - SWA Control Specification UHP 520.1, technique SWATS 141

- Powder – Amperit 526.062/895
- Fuel – Hydrogen
- SWA Control Specification UHP 545, technique SWATS 140
- Powder – Sulzer Metco 5847
- Fuel – Hydrogen

Testing was done in three test Sequences as shown in Table 3-61, with the coating varying for each Sequence.

Sequence 1 coating:

Specimens were coated over most of the gauge length, as shown in Figure 3-94. Specimens were **not** ground, so as to represent a typical post-plating hydrogen bake prior to grinding. The EHC-coated specimens in the second column of Table 3-61 Sequence 1 were hydrogen baked (within 4 hours of plating), while column 1 specimens were not.

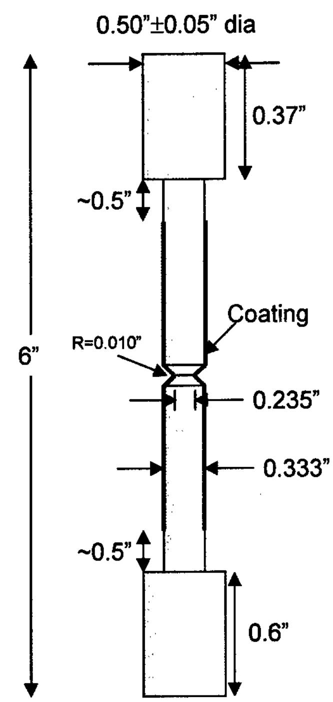


Figure 3-94. Standard F-519 Specimen Coating

Sequence 2 coating:

This Sequence required charging the specimen with hydrogen, which was accomplished by bright Cd plating and stripping without baking. Coating was as follows:

- The entire specimen was bright Cd plated to a thickness of 0.0002-0.0005" in accordance with BAC 5701.
- Within 4 hours of plating the Cd was chemically stripped in the gauge section to a distance of approximately 0.7" from the end cap.
- The exposed surface was grit blasted for HVOF coating.
- Within 6 hours of Cd plating, HVOF was coated over the gauge section, overlapping the Cd on the ends, per Figure 3-94. The specimen was completely coated – with HVOF in the gauge section, and bright Cd on the ends.
- For specimens in Sequence 2, column 2 (Table 3-61), a hydrogen bakeout (24 hrs at 375°F) was done within 4 hours of coating.

Specimens were **not** ground.

Sequence 3 coating:

Specimens were coated as in Figure 3-94, and the coating ground to a 16μ" (Ra) finish. The coating in the notch was not ground.

During HVOF spraying, the overspray material, which would normally bounce back off the surface, tended to become trapped in the notch, producing a thicker and more porous coating. This entrapment was minimized by directing a strong air stream into the notch

and by spraying with the gun at an angle of 30° to the normal. During HVOF coating the specimen was rotated while the gun was traversed, angling the gun at +30° from the normal when traveling in one direction and -30° when traveling in the other.

3.7.5. Scribing (exposing the notch to the test environment)

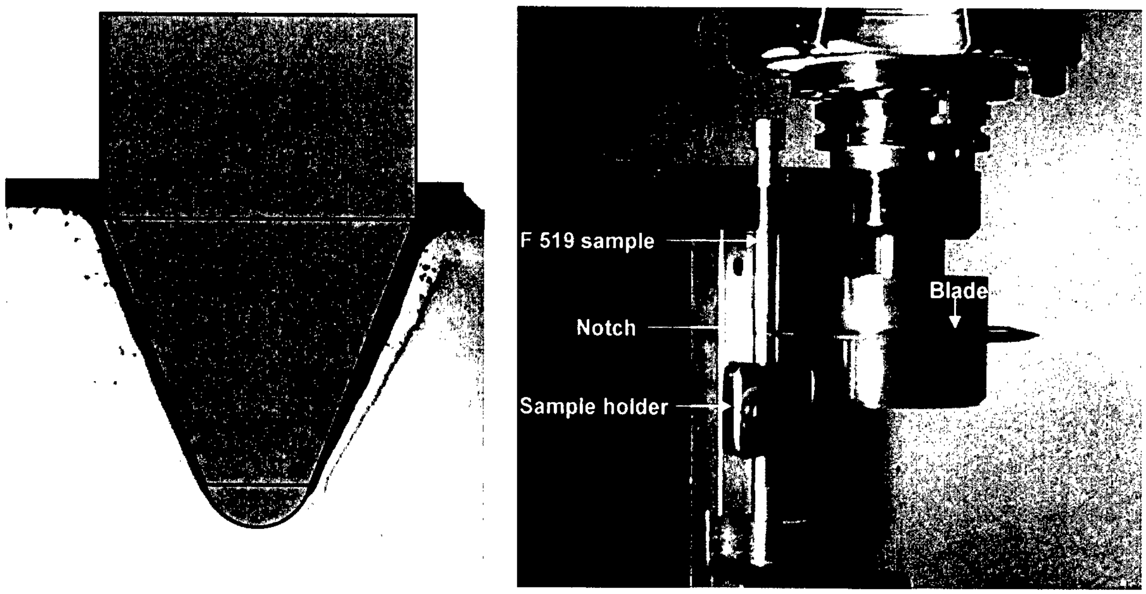


Figure 3-95. Method for Scribing the Notch (exposing the substrate) on a CNC Milling Machine (Left – schematic of cutting blade in notch; right – actual set-up on CNC machine)

The standard method used for scribing the notch is to cut through the coating with a diamond file. This works well for soft coatings but was not possible with hard HVOF coatings or hard chrome plating. Therefore a new method was developed using a commercially available shaped circular blade with a 45° angle and a 0.010" radius OD, which was coated with diamond. The method is illustrated in Figure 3-95. The blade was driven into the notch to cut just into the underlying steel. It was then rotated around the sample and withdrawn 45° away from the starting point, exposing a 45° segment of the substrate metal in a reliable and reproducible manner. Each scribed substrate was visually examined at 10x to ensure complete coating removal in the scribed area before the specimen was removed from the machining holder.

3.7.6. Test methodology

Specification:	ASTM F-519, "Mechanical hydrogen embrittlement evaluation of plating processes and service environments"
Modifications:	Various modifications of sample preparation as described in text.
Significance:	Embrittlement is a primary failure mechanism for landing gear.
Sample types:	F-519 Type 1a.2 notched bar:
	Length: 6"
	Gage OD: 0.333"

Notch angle: 60°

Notch depth: 0.049"

Notch radius: 0.010"

Sample materials: 4340 per MIL-S-5000

Sample heat treat: 52 R_c

Coatings: EHC, WC-Co, WC-CoCr, as-sprayed, and ground

Coating thicknesses: 0.003" and 0.010"

Test equipment: Static load creep rupture frame – one specimen per frame.

- **Test description:** All tests were run under static load in air or in solution, depending on the experimental Sequence, as described in Table 3-61. Tests were stopped at 200 hours unless the specimen failed (broke) before this.

For Sequences 1 and 2, samples were tested as-coated at 75% NTS. For Sequence 3, samples were tested at 45% NTS. During Sequence 3 tests, the test solution covered only the central portion of the gauge section, excluding any areas outside the coating.

In all cases, because coating and testing were done in different locations, several weeks passed between coating and testing.

Table 3-61. Hydrogen Embrittlement Test Matrix

	Sequence 1		Sequence 2		Sequence 3			
	Baseline		Hydrogen pre-test loading		Environmental embrittlement (re-embrittlement) in standard solutions			
Pretest H load	No	No	Yes	Yes	No	No	No	No
Test environment	Air	Air	Air	Air	DI H_2O	DI H_2O	5% NaCl	5% NaCl
Hydrogen bake	No	Yes	No	Yes	No*	No*	No*	No*
Grind coating	No	No	No	No	Yes	Yes	Yes	Yes
Notch partly exposed						Yes		Yes
Load (% of NTS**)	75%	75%	75%	75%	45%	45%	45%	45%
Coatings:								
None	3		3	3		6		6
Hard chrome, 0.003"	3	3			3	6	3	6
WC-Co, 0.003"	3		3	3	3	6	3	6
WC-Co-Cr, 0.003"	3		3	3	3	6	3	6
Hard chrome, 0.010"	3	3			3		3	
WC-Co, 0.010"	3		3	3	3		3	
WC-Co-Cr, 0.010"	3		3	3	3		3	
Total samples	21	6	15	15	18	24	18	24

* Chrome plated specimens hydrogen baked, HVOF specimens not baked

** Loads determined by testing (see Table 3-63).

3.7.7. Test sample mechanical properties

Prior to embrittlement testing, the specimens were tested to verify Rockwell hardness and to determine their notch tensile strength (by loading to failure). Table 3-62 and Table 3-63 show the

Table 3-62. F-519 Test Specimen Hardness

Sample #	Rc hardness
H 2015	52
	51.9
	51.9
H 2494	52.1
	51.6
	52.2
H 2567	51.8
	51.7
	51.9
Average	51.9

Table 3-63. F-519 Test Specimen Notch Tensile Strength

Sample #	NTS, ksi
H2494	362
H2015	372
H2567	383
H2281	370
H2537	380
NTS	373
75% NTS	280
45% NTS	168

hardness and notch tensile strength results.

3.7.8. Coating structure

Chrome plating into the notch produced a coating whose thickness in the groove bottom was 20%-50% that on the outer surface (see Figure 3-96, top picture). The HVOF coating in the base of the notch (Figure 3-96, bottom picture) was 2.5 - 7 times thicker than on the outer surface and had a layered structure with high porosity. This structure appears to comprise relatively dense layers sprayed directly into the notch, interleaved with porous overspray material.

The cross-sectional details of HVOF WC-Co and of EHC in the notch are shown in Figure 3-97. The HVOF layering was only present in the notch, while the coating structure on the OD was that of a typical dense HVOF coating.

Both EHC and HVOF coatings in the notch were left as-deposited because of concern that any machining or grinding in the notch would have been likely to lead to uncontrolled cracking or other specimen damage.

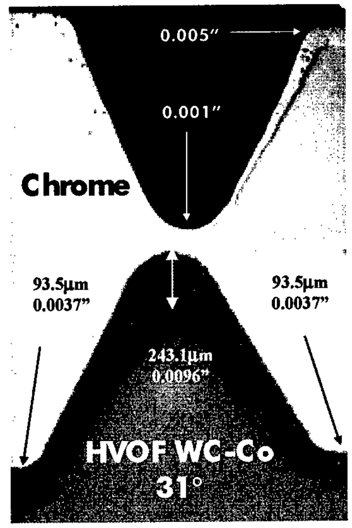


Figure 3-96. EHC and HVOF WC-Co in Notch of F-519 Specimens

3.7.9. Test results

3.7.9.1. Cracking of coatings

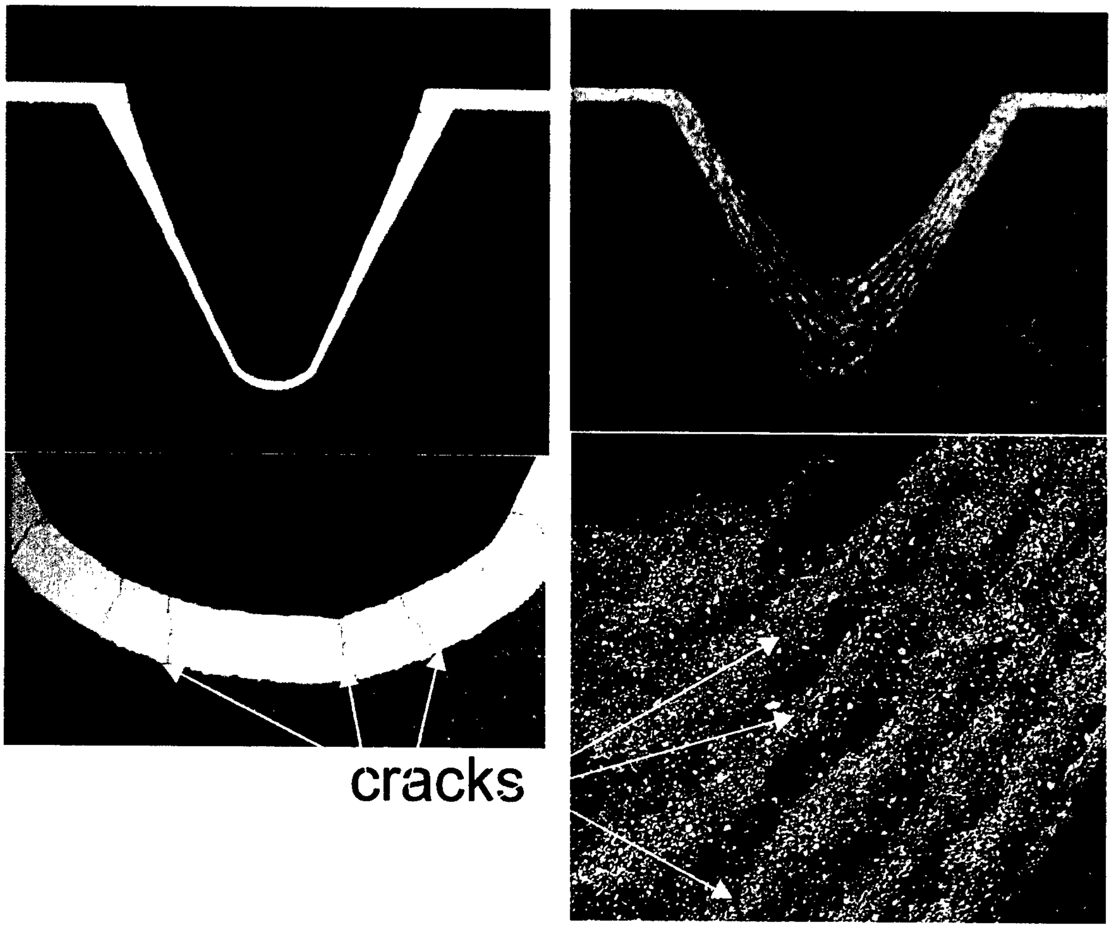


Figure 3-97. Metallographic Cross Sections of Chrome Plate (left) and HVOF WC-Co After Stressing to 45% NTS in Air (Note also the original layer formation in the HVOF coating)

On stressing to 45% NTS both the chrome and HVOF coatings cracked (Figure 3-97). The chrome plate exhibited many fine cracks around the notch radius, but the WC-Co showed only a few cracks penetrating to the substrate. After stressing, liquid penetration to the substrate would be expected through cracks in the chrome plate and through both cracks and porosity in the HVOF coating.

3.7.9.2. Substrate failure mechanisms

In Sequences 1 and 3 all failures were in the notch. All Sequence 2 failures were shank failures at the button (cracks emanating from the join between the button end and the gauge section), with the exception of a notch failure specimen H1216 (a specimen coated with 0.010"-thick WC-CoCr), which failed because of overloading.

Sequence 3 failure surfaces were examined metallographically. Specimens that failed on loading showed no sign of embrittlement (i.e. they failed by overload instead of

embrittlement), while the rest of the Sequence 3 specimens showed the following results:

Bare specimens:

- ❑ Single site nucleation; thumbnail-like appearance in test environment
- ❑ Crack length (depth) about 1/4 notch diameter deep by 1/2 notch diameter wide
- ❑ Classic intergranular fracture surface

Chrome plated specimens:

- ❑ Multiple through *(surface to substrate)* cracks occurred in the Cr plating at the notch when loaded to 45% of NTS in air
- ❑ Multiple nucleation sites around notch in test environment
- ❑ Shallow multiple-cracks approximately 1/8 notch diameter deep around most of circumference
- ❑ Classic intergranular fracture surface

HVOF coated surfaces:

- ❑ Some cracking of coatings at notch when loaded to 45% NTS
- ❑ Single site nucleation; thumbnail-like appearance in test environment
- ❑ Crack length (depth) about 1/4 notch diameter deep by 1/2 notch diameter wide
- ❑ Classic intergranular fracture surface

In contrast to expectations, Sequence 3 crack initiation sites were most frequently <u>not</u> associated with the exposed substrate produced by scribing in the scribe. This is summarized in Table 3-64.

Table 3-64. Summary of Crack Initiation Points

Coating	**Unscribed area of notch**	**Scribed area of notch**	
		Crack assoc. with scribe	Crack *not* assoc. w/scribe
Bare	6 specimens – thumbnail shaped crack	N/A	
Cr plating	12 specimens – shallow circumferential crack	none	6 specimens
WC-Co	24 specimens – thumbnail shaped crack	1 specimen	5 specimens
WC-Co-Cr		3 specimens	3 specimens

3.7.9.3. Time to failure data

The test results are summarized in Table 3-65 and Figure 3-98 to Figure 3-104. The full data set summary is provided in Appendix 6 of the JTR [3.1]. The graph bars show the

average Time-to-failure values. Because there were only three data points per condition, where error bars are given in these charts, they indicate the data range (high and low values), rather than the standard deviation.

Table 3-65. F-519 Hydrogen Embrittlement Testing – Average Time to Failure (NF = No Failure in 200 hr)

	Sequence 1		Sequence 2		Sequence 3			
					Distilled water		5% NaCl solution	
	Not baked	Baked	Not baked	Baked	Unscribed	Scribed	Unscribed	Scribed
None	NF		NF	NF		33.8		15.3
EHC, 0.003"	0	NF			0.1	2.2	0.1	0.1
WC-Co, 0.003"	NF		6	139	4.7	9.8	3.4	6.8
WC-Co-Cr, 0.003"	NF		6	NF	15.6	36.8	8.3	14.3
EHC, 0.010"	0	214			0.1		0.1	
WC-Co, 0.010"	NF		6	NF	5.0		3.6	
WC-Co-Cr, 0.010"	NF		27	NF	19.4		4.8	

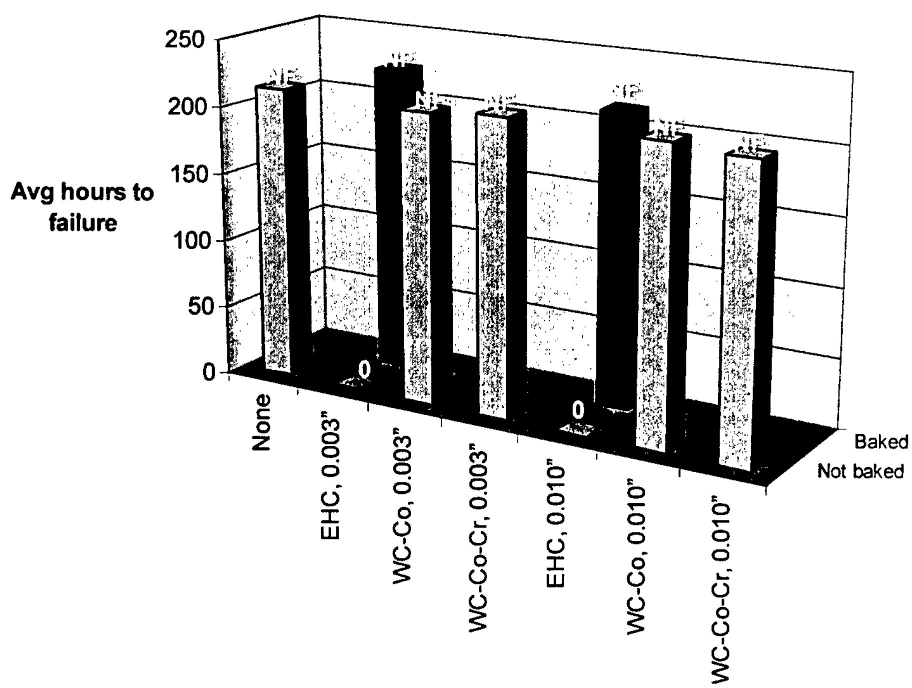


Figure 3-98. Sequence 1: Average Hours to Failure (NF = No failure in 200hrs), With and Without Hydrogen Bake (All failures in notch)

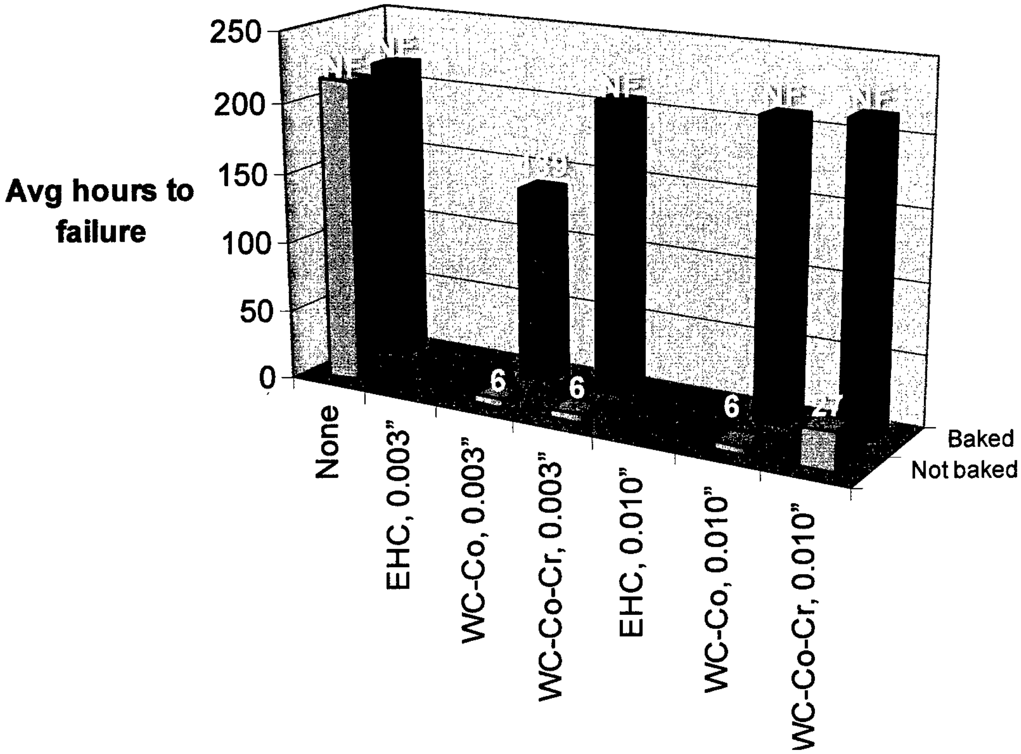


Figure 3-99. Sequence 2: Average Hours to Failure (NF = No failure in 200hrs), With and Without Hydrogen Bake (Failures occurred on shank at button)

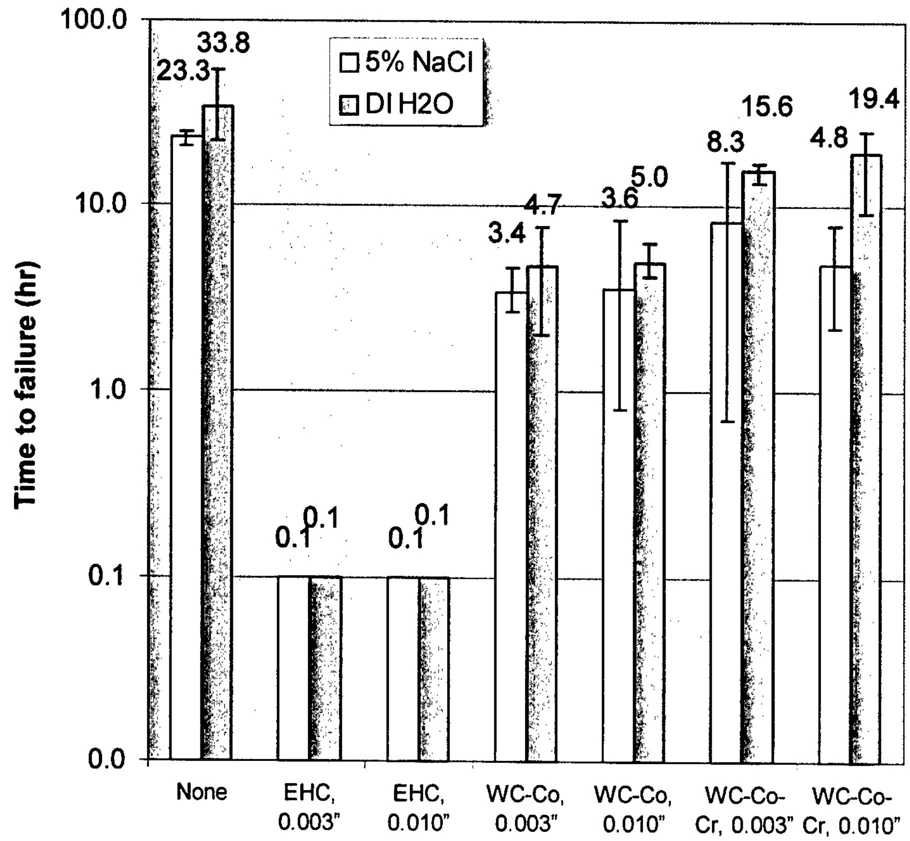


Figure 3-100. Sequence 3 Average Hours to Failure With No Notch Scribing. (Numbers are average time-to-failure data values – note log scale; error bars indicate high and low values)

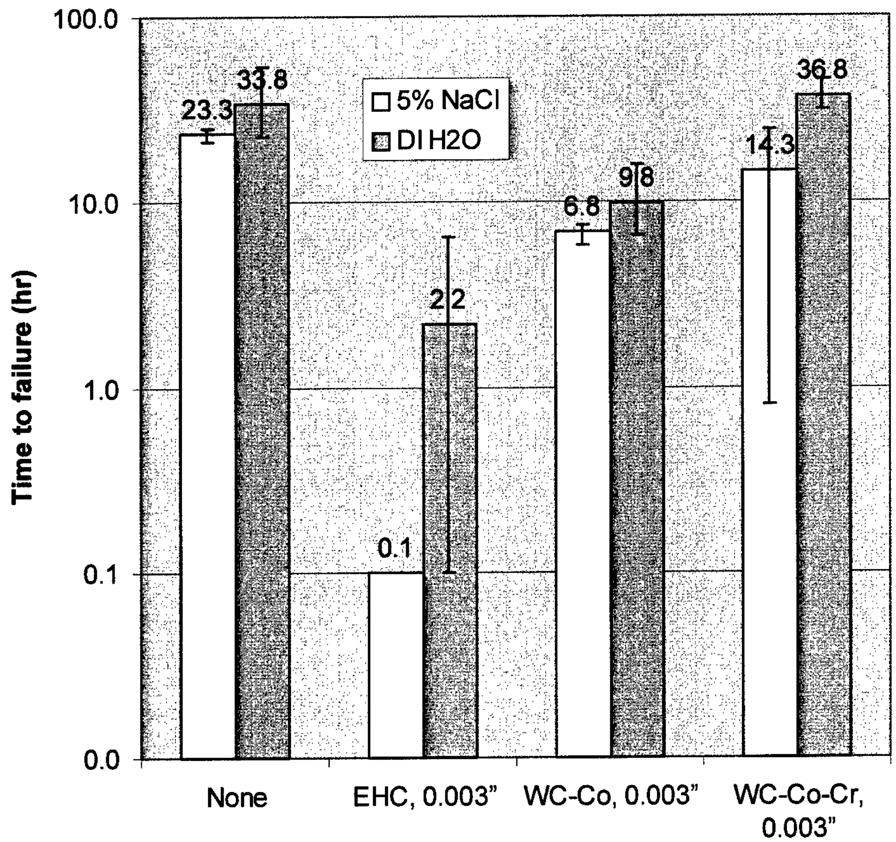


Figure 3-101. Sequence 3: Average Hours to Failure With Notch Scribed to Expose the Substrate (Numbers are average time-to-failure data values – note log scale; Error bars indicate high and low values) (Note that these tests were run for 0.003"-thick coatings only)

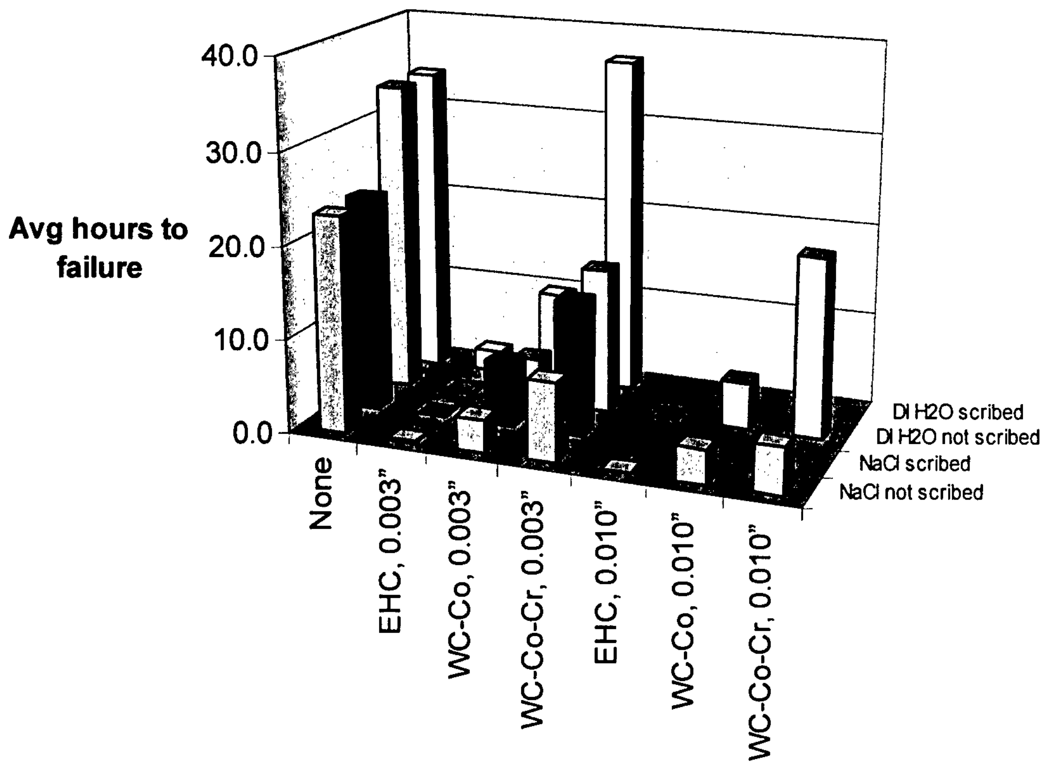


Figure 3-102. Sequence 3 Time-to-failure Data Summary

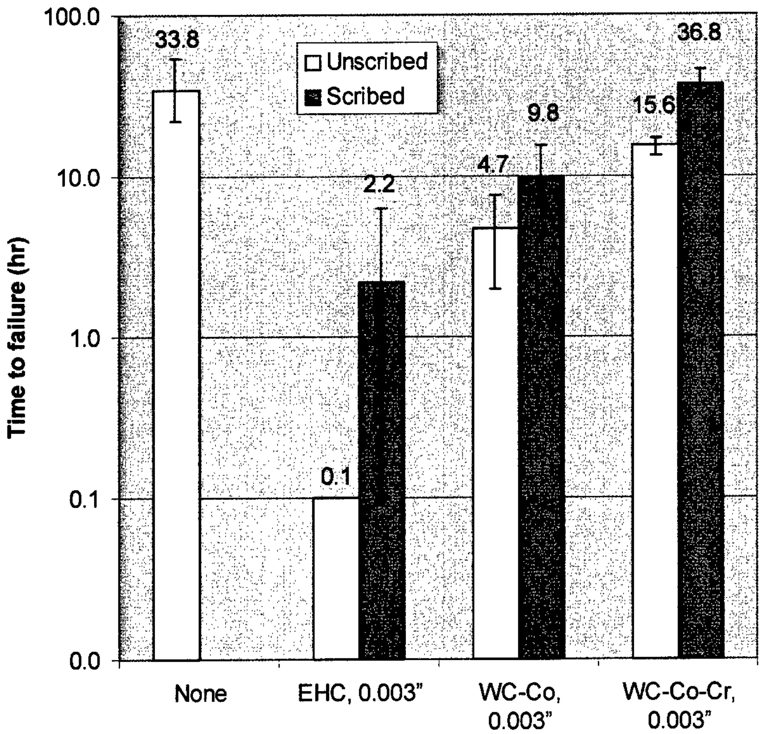


Figure 3-103. Sequence 3 – Comparison of Time to Failure for Scribed and Un-scribed Specimens - DI Water

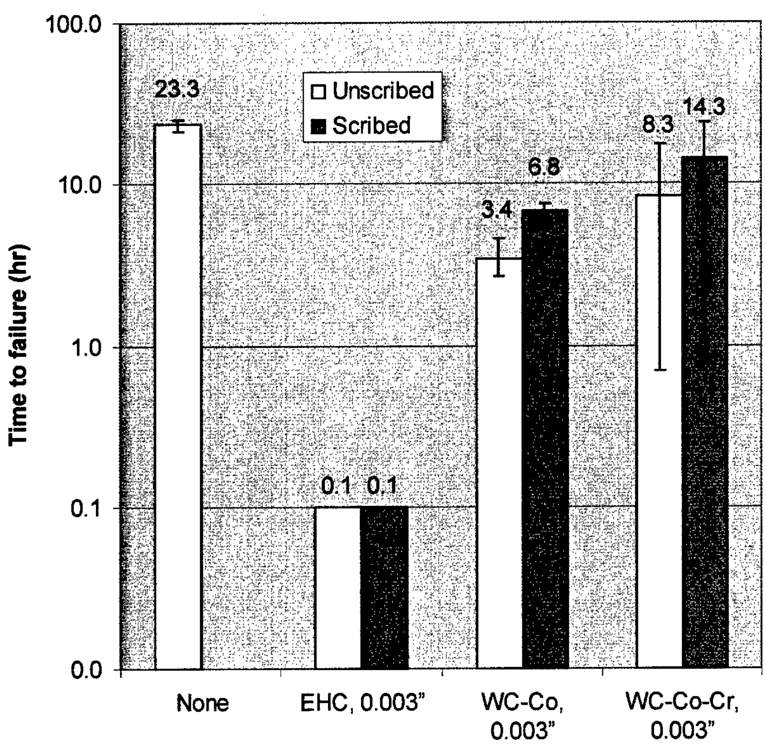


Figure 3-104. Sequence 3 – Comparison of Time to Failure for Scribed and Un-scribed Specimens - 5% NaCl Solution

3.7.9.4. Open circuit potential

Open circuit potentials were also measured as a function of time for rods and unscribed coated sheets in 5% NaCl solution. Figure 3-105 shows the results for 100 hr exposure. Plotting time-to-failure against this long term average potential difference gave the graph of Figure 3-106.

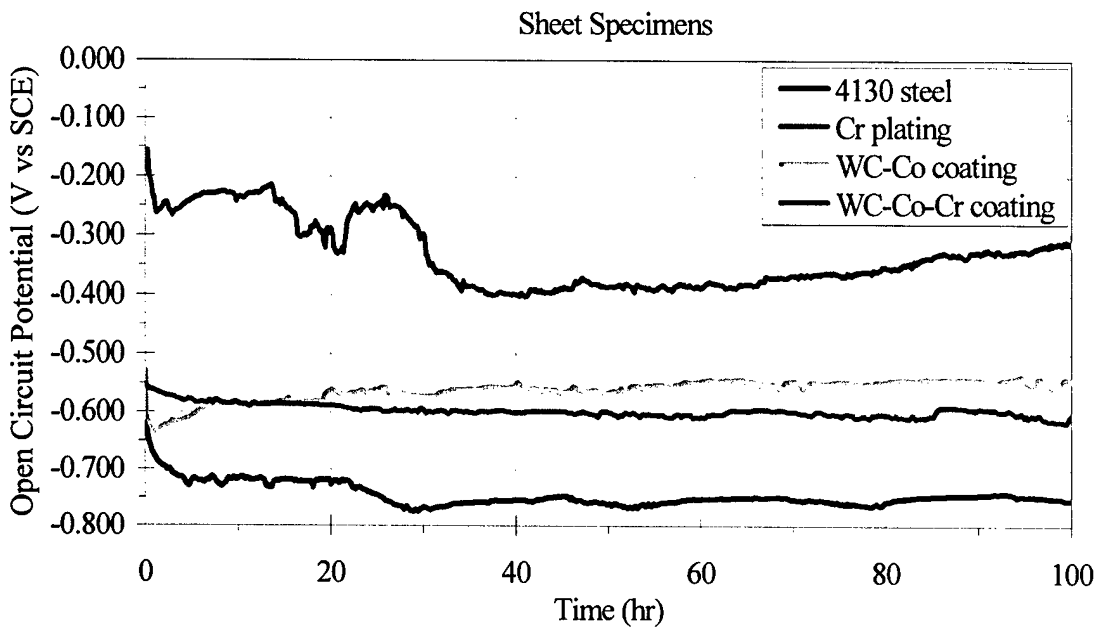


Figure 3-105. Open Circuit Potential for Coated Sheet Specimens in 5% NaCl Solution

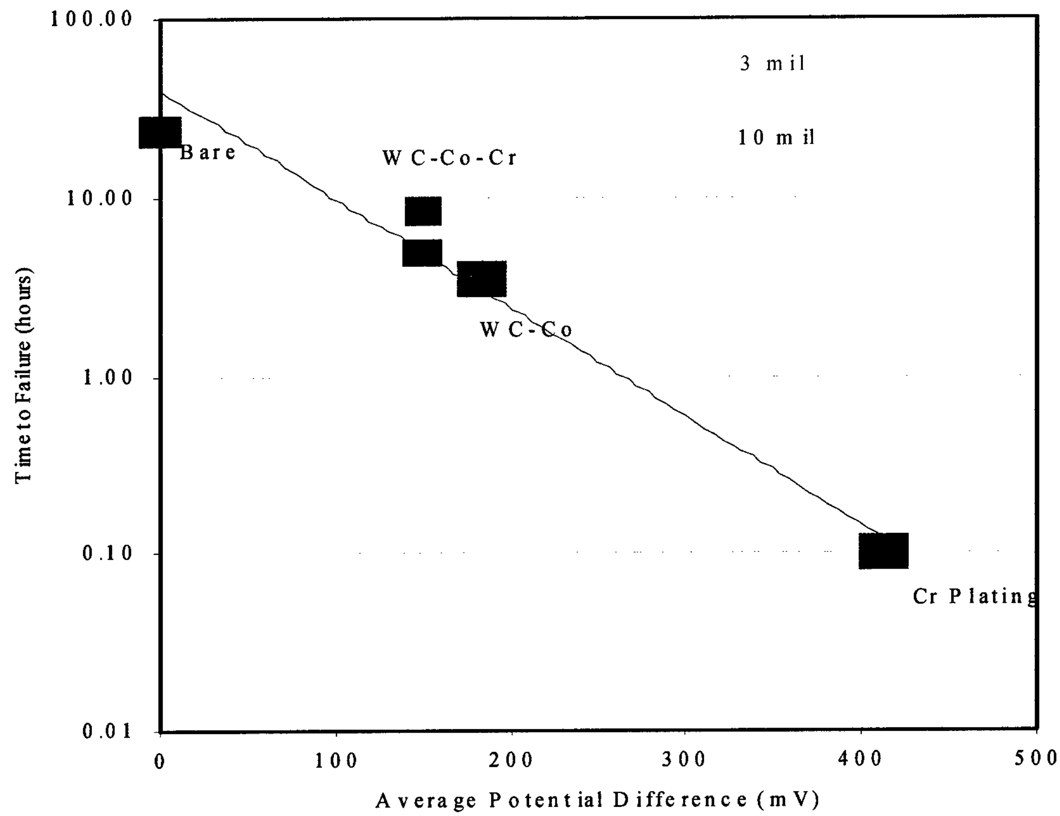


Figure 3-106. Plot of Log Time-to-failure vs. Average Potential Difference Between Coating and 4340 Substrate in 5% NaCl Solution

3.7.10. Discussion of hydrogen embrittlement results

Sequence 1: Figure 3-98 shows that chrome plated specimens fail very rapidly due to hydrogen embrittlement if they are not baked, but pass when baked. HVOF coated specimens pass with or without baking. Therefore the HVOF coating process does not cause hydrogen embrittlement.

Sequence 2 is more complex. Figure 3-99 shows that hydrogen-charged specimens failed within a few hours without baking, but mostly passed when baked. (Note that this Sequence did not include chrome plated specimens since it is already known that hydrogen baking after chrome plating is required to remove the hydrogen and prevent embrittlement.)

(Note that specimens that were Cd-plated, stripped in the gauge section, but not recoated or baked did not fail when tested several weeks later, whereas the traditional expectation is that they would fail very quickly. On the other hand Sequence 1 samples that were chrome plated but not baked, and also tested after several weeks failed very rapidly. This suggests that the hydrogen diffuses slowly out of an uncoated surface over time, but

remains trapped if the surface is coated.)

Without baking the HVOF-coated specimens exhibited shank/end failures (i.e. failure on the shank at the button, not at the notch). This means either

1. that the notch K_t was reduced because the coating blunted the notch and carried some of the load, moving the highest stress point to the shank/end, or
2. most of the hydrogen was driven out from the notch by the local surface heating during the HVOF process, but this did not remove the hydrogen beneath the bright Cd at the ends of the specimen, because those areas were not heated by the HVOF flame. Failure therefore occurred at the shank/end.

Metallography shows that the HVOF coating in the notch cracks at 45% NTS, preventing its supporting the load and reducing the K_t. Furthermore, the material was very porous and would have had poor mechanical properties, also reducing its ability to carry load. Based on this together with the data for Sequence 3 (discussed below) we believe the lack of notch failures to be entirely due to factor 2 above.

With baking most of the specimens passed the test. Those that did not pass failed at the button. We interpret this to mean that the hydrogen at the high stress join between button and shank diffused out through the adjacent HVOF coating, since hydrogen cannot readily diffuse through bright Cd. Those samples that still failed did not have the hydrogen fully removed, probably because of insufficient bakeout time (i.e. the long time required to diffuse hydrogen either along the long path between the button and the HVOF-coated region or to diffuse it through the bright Cd). Note that the loss of hydrogen from the button/shank join on baking suggests that if most of the hydrogen diffused through the HVOF coating, it would have done so primarily through the high-quality coating on the gauge section adjacent to the Cd-plated end, not through the poor quality coating in the notch, which was much further away. Therefore, hydrogen appears able to diffuse through high-quality HVOF coatings.

Sequence 3 clearly shows that hard chrome performs very poorly in this type of test. HVOF coatings perform much better than chrome, with WC-CoCr outperforming WC-Co, as expected. Figure 3-100 shows time to failure for samples with the notch not exposed (i.e. unscribed), while Figure 3-101 shows time to failure with the notch partially exposed (i.e. scribed). All of the data are summarized in Figure 3-102 for comparison.

Figure 3-100 (unscribed coatings) shows the following:

- ❑ While the specimens failed sooner in NaCl there was little difference between time to failure in 5% NaCl solution or distilled water.
- ❑ Coating thickness had no significant effect on time to failure.
- ❑ Failure occurred in EHC specimens within minutes – very much sooner than HVOF-coated specimens.
- ❑ WC-CoCr had slightly increased time-to-failure than WC-Co.

The relative time-to-failure performance of the HVOF coatings and chrome plating can be understood in terms of the open circuit potential difference between the substrate and

the coating. Figure 3-105 shows that EHC has a much larger potential difference from the 4340 substrate than either HVOF coating, and over the long term the potential difference of EHC>WC-Co>WC-CoCr. When log time-to-failure is plotted versus this potential difference (Figure 3-106) the result is roughly linear, with the shortest time-to-failure being given by the largest galvanic potential difference.

The data for scribed specimens (Figure 3-101) show results that are similar to the unscribed specimens, with HVOF coatings far outperforming EHC (note that a single EHC sample lasted 6 hours, while all others lasted less than 10 minutes). Again, WC-CoCr slightly outperformed WC-Co. **However, the data show that the scribed specimens in general outperformed the un-scribed specimens** (see Figure 3-102 to Figure 3-104), **but the time-to-failure of the uncoated specimens was longer than both**.

The data from scribed coatings, in which coating was removed around a quarter of the notch to expose the substrate, are more difficult to understand. One would have expected *a priori* that clear exposure of the surface would enhance substrate corrosion in the exposed area, and hence hydrogen generation (and with it embrittlement). One would therefore have expected that specimen failure cracks would be associated with scribes. However, in general this is not the case (Table 3-64).

We believe that cracks in the substrate occurred in unscribed areas because corrodant could easily penetrate through cracks and porosity in the chrome and HVOF coatings. With corrodant easily reaching the metal substrate, the galvanic coupling effect is greater in coated (un-scribed) areas, because. the ratio of the cathodic coating area to the anodic substrate area is higher, and the anode and cathode are in very close proximity. This creates higher potential gradients with higher corrosion current densities and hence more local hydrogen. In contrast the scribed areas have lower current densities and hence a lower local hydrogen concentration.

A question arises as to the effect of the poor quality of the HVOF coatings (thick, layered, high porosity) in the notch. It has been suggested that the combination of the thick coating in the notch that will lower the K_t, and the high elastic modulus of the coating will lead to much longer time-to-failure. On the other hand we might well expect that a porous coating in the notch will make corrosive attack easier and reduce time-to-failure. We can draw some inferences from our data:

- As noted above, the thickness of the HVOF coatings in the notch could have reduced the K_t by increasing the notch radius. The fact that failures occurred at all (and especially occurred in a few tens of hours) implies that any diminution of K_t was fairly small.
- When the coating was scribed, the true K_t was re-established in the scribed area because the notch was recut to the correct (smaller) radius. Rather than being reduced, which is what we would expect on sharpening the notch, the time-to-failure of notched specimens actually increased, again showing that the thick HVOF coating in the notch did not lower K_t. Furthermore, cutting through the coating would have eliminated any effect due to elastic modulus, because the coating was no longer continuous and therefore no longer able to carry load. If the elastic modulus of the coating had contributed to increased time-to-failure

then failure time should have dropped on scribing, not risen.

- We would expect a similar electrochemical potential between the substrate and either good quality or poor quality HVOF coatings, since the coating chemistry is the same. Therefore we would not expect any effect due to electrochemical potential, as seen between HVOF and hard chrome in Figure 3-105 and Figure 3-106.
- With low quality, porous HVOF coatings, liquid should penetrate to the substrate through the pores, as well as through the cracks that form on loading (which can be seen in Figure 3-97). With high quality, low porosity HVOF coatings, liquid will penetrate to the substrate primarily through the cracks that form on loading. We cannot tell *a priori* which type of coating will have higher time-to-failure, although it would be reasonable to expect that the more porous, lower quality coating would show shorter time-to-failure.
- Therefore, although we cannot make a firm conclusion on the overall effect of the poor HVOF quality in the notch, we can say that **it did not increase time-to-failure by decreasing the K_t or by providing a high-modulus surface layer.**

Therefore, although the quality and thickness of the HVOF coatings in the notch reduced the reliability of the results, it does not appear to have invalidated the overall trend.

3.7.11. Significance

These results imply the following

- Since the HVOF process does not cause hydrogen embrittlement, it avoids any technical need for stress relief baking prior to coating (which is done to prevent HE during plating) as well as for hydrogen baking after (to prevent subsequent HE failure).
- Since hydrogen can diffuse through HVOF coatings during a hydrogen bakeout, we would expect it to be possible to strip and electroplate areas adjacent to HVOF coatings without trapping the hydrogen and creating an embrittlement problem. This makes it a little easier to conduct depot maintenance, although in practice only Cr and LE Cd are generally used on high strength steels, both of which permit diffusion of hydrogen during baking.
- The reduction in galvanic coupling on HVOF coated parts should reduce the incidence of environmental hydrogen embrittlement and stress corrosion cracking. Use of HVOF WC-Co in place of hard chrome should therefore reduce both post-maintenance HE failure and subsequent stress corrosion failure in service. According to OO-ALC and the Air Force Aging Landing Gear Life Extension Program, these are two common failure mechanisms for military landing gear.

3.7.12. Conclusion

Sequence 1 – The HVOF coating process does not cause hydrogen embrittlement. **Passes acceptance criteria.**

Sequence 2 – Hydrogen diffuses through HVOF coatings at 375°F, making it easier to strip and plate areas adjacent to them without trapping hydrogen and causing embrittlement. However, diffusion through HVOF coatings may occur at a slower rate than diffusion through EHC, and may therefore require a longer hydrogen bakout of any non-porous coating electroplated contiguous with an existing HVOF coating. Since the data on this point are not definitive, additional testing may be needed to verify this. **No pass/fail criterion.**

Sequence 3 – HVOF coatings perform much better than chrome under galvanic coupling conditions likely to cause environmental hydrogen embrittlement. **Passes acceptance criteria.**

3.8. Summary and Conclusions

- **Fatigue**
  - The fatigue lives of landing gear steels coated with HVOF WC-17Co are in all cases equal to or better than those coated with EHC.
  - The HVOF coatings develop a circumferential crack pattern, and in some cases spall at high loads.
    - This coating integrity issue of cracking, delamination, and spalling is presently under detailed investigation, and the results will be reported when they are completed. Early data indicates that this behavior is a strong function of deposition conditions and coating thickness. Under axial stress, 0.003"-thick WC-17Co have retained their integrity to yield (220ksi) at R= -1, while 0.012"-thick coatings have spalled. Under very limited R= -0.33 bending load testing, 0.010"-thick WC-Co coatings have survived to stresses above yield. Thus the problem appears not to be an OEM issue, but to be an issue primarily for thick repair coatings, and will require the definition of reliable repair schemes involving monolithic or duplex coating structures.
- **Corrosion**
  - Corrosion results are highly variable. HVOF coatings clearly provide significant protection against corrosion. However, while pre-JTP work showed significantly better performance for HVOF, the JTP work and supplementary evaluations showed WC-Co and WC-CoCr performance as being inferior to EHC.
    - Since EHC is highly variable in corrosion performance, and since the chrome baseline material appeared to be exceptionally corrosion-resistant, we cannot draw conclusions on how HVOF coatings compare with EHC commonly used in the DOD repair community.
    - Combining data from our corrosion and embrittlement testing we conclude the following: EHC coatings do not corrode, but permit substrate corrosion through cracks and other imperfections. The Co binder in WC-Co coatings can itself corrode. The corrosion mechanism is therefore different between the two materials. In WC-CoCr the corrosion of the CoCr binder appears to proceed at a rate intermediate between that of Co and that of Cr.
- **Wear**
  - Fretting tests were found not to be useful discriminants between coatings, but sliding rod/bushing wear tests could discriminate.
  - Although detailed statistical analysis has not been done, the overall conclusion is that HVOF WC-Co and WC-CoCr coatings show less wear

than EHC, but that they tend to cause more wear on bushings. This is consistent with various rig and flight tests, and the industry has generally reduced bushing and seal wear (usually below that caused by chrome) by superfinishing the HVOF coatings.

- There was no significant difference between the performance of WC-Co and WC-CoCr.

- **Impact**
  - The performance of both WC-Co and WC-CoCr was better than EHC in both gravelometry and dropped ball impact.
    - These measurements relate only to damage sustained on impact and do no address the subsequent performance of the material.

- **Hydrogen embrittlement**
  - HVOF does not cause embrittlement during deposition
  - Hydrogen can diffuse through HVOF coatings to permit embrittlement-relief heat treatment of electroplating or stripping operations subsequent to HVOF coating, although the diffusion rate may be slower than through EHC.
  - In environmental embrittlement testing WC-Co performed very significantly better than EHC, while WC-CoCr was slightly better than WC-Co.
    - These data are understandable in terms of the electrochemical potentials of the coating materials.

3.9. References

3.1 "Joint Test Report, Validation of WC/Co and WC/CoCr HVOF Thermal Spray Coatings as a Replacement for Hard Chrome Plating on Aircraft Landing Gear, Part I: Materials Testing," Prepared by Hard Chrome Alternatives Team for Environmental Security Technology Certification Program, November 2002 (available from www.hcat.org)

3.2 P. M. Natishan, S. H. Lawrence, R. L. Foster, J. Lewis and B. D. Sartwell, "Salt Fog Corrosion Behavior of High-Velocity Oxygen-Fuel Thermal Spray Coatings Compared to Electrodeposited Hard Chromium," Surface and Coatings Technology, v. 130, pp. 218-223 (2000).

3.3 Jay Randolph, Delta Airlines, "Service Evaluation Status and Impact of HVOF Coatings on Landin Gear at Delta Airlines," Gorham Advanced Materials Conference on Advanced Coating Systems for Gas Turbine Engines and Aircraft Components, San Antonio, March 2000

3.4 Tony DeGennaro, Green, Tweed & Co., "Evaluation of Chrome Rod Alternative Coatings," Report #GTE0644, September 1999

3.5 Naval Air Warfare Center Aircraft Division Report No. NAWC-ADLKE-DDR-481400-0001

4. Coating Integrity and Spalling

The coating integrity issue was first reported by C-HCAT when fatigue testing WC/CoCr specimens. They found that above a certain stress coatings tended to delaminate and that the stress at which this occurred was lower for thicker coatings. The finding led to extensive testing to understand and quantify the phenomenon.

The Canadian team carried out extensive materials analysis and concluded that when the strain-to-failure of the coating was exceeded it would crack on the tensile cycle and the cracks would propagate into the coating to the interface with the underlying steel, where they would bifurcate and spread through the coating parallel to the interface. Eventually the cracks would spread far enough for the coating to delaminate, usually during a compressive cycle.

4.1. Axial integrity tests

Initial findings were made with standard 0.25" diameter fatigue specimens. Because of concern over whether coatings made on such small diameters were truly representative of those made on larger items, additional tests were run on 2" diameter hollow bars (Figure 4-1 and Figure 4-2). However, data obtained from the large and small bars showed that the coating integrity behavior was very similar.

The team has carried out testing on three primary materials:

- WC/Co (HCAT and NAVAIR)
- WC/CoCr (HCAT, small bars)
- T400 (HCAT)

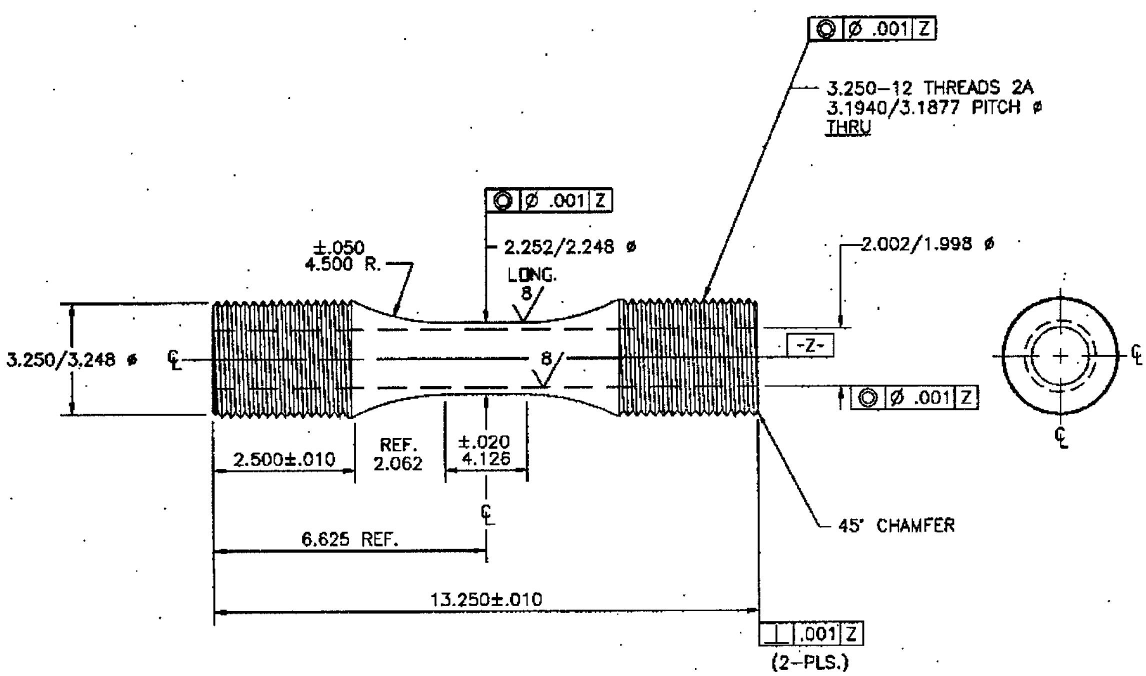


Figure 4-1. HCAT Axial Integrity Big Bar Design (Metcut)

In general it has been found that the spalling threshold for WC/10Co4Cr is lower than for WC/17Co, presumably because the WC/Co has more matrix metal, making it more ductile.

However, more metallic materials, such as T400, do not show significantly superior integrity. As a result the team is currently engaged on a Process Mapping program funded by HCAT, ALGLE, and the thermal spray companies (Deloro Stellite, Sulzer Metco, and Praxair) to develop test methods capable of predicting spalling behavior. These methods will in turn be used in the development of higher integrity materials. Initial data from these tests indicates that the initial WC/CoCr optimization used for the Canadian tests accidentally had the effect of significantly reducing the ductility of the coating [4.1].

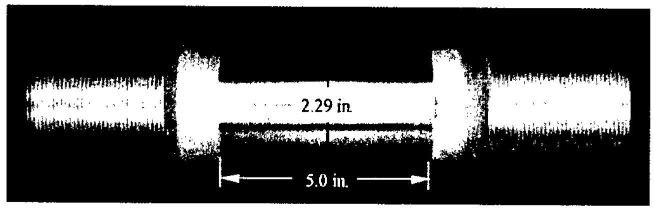


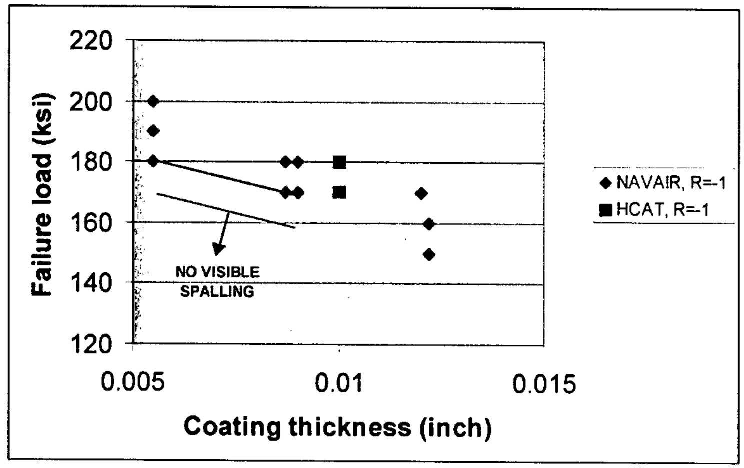
Figure 4-2. NAVAIR "Big Bar" Axial Integrity Test Specimen (Eui Lee, NAVAIR)

Tests have been run using large bars at R= -1, which NAVAIR [4.2] chose to simulate carrier landings, and at R= -0.33, which OO-ALC [4.3] chose to simulate land-based aircraft landings. Specimens were subjected to several cycles at stepped loads until spalling occurred.

The results are shown in Figure 4-3. It can be seen that the HCAT and NAVAIR tests are similar, but that thresholds vary considerably. Note that spalling occurs at lower stress for higher coating thickness and in general R= -1 conditions cause spalling at lower stress than R= -0.33. The areas below the red lines are considered by NAVAIR to be the operating regions of stress and coating thickness in which spalling will not occur.

In axial tests the coatings tended to "rumple" somewhat prior to failure, and then to delaminate over most of the surface simultaneously.

On this basis NAVAIR have so far concluded that for most cases they are not comfortable with the use of HVOF coatings for landing gear on carrier-based aircraft, although land-based Naval aircraft and helicopters do not appear to be a serious issue.



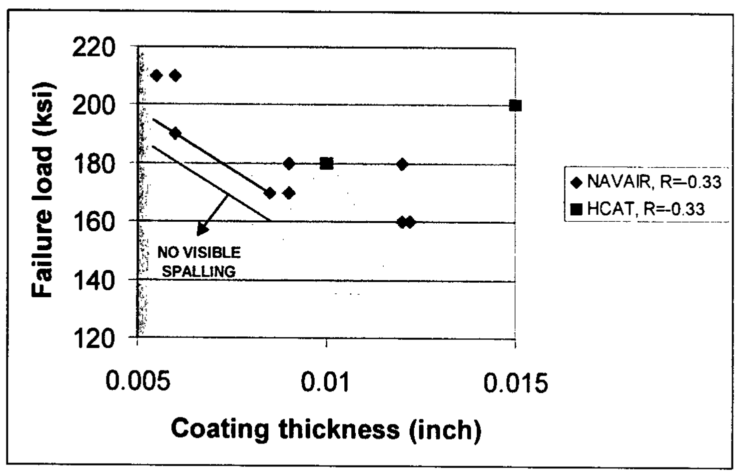


Figure 4-3. Axial Big Bar Integrity Tests (HCAT and NAVAIR).

4.2. Landing gear bend integrity tests

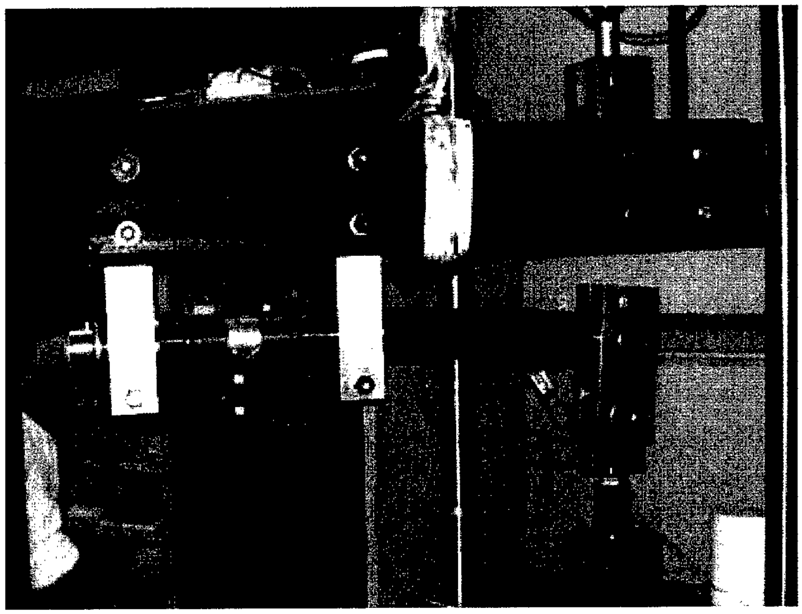


Figure 4-4. Hill AFB Bend Test Fixture

Ogden ALC has taken the approach that the test configuration should mirror the service conditions, in that almost all major landing gear components are tubes that experience bending stresses rather than tensile stresses (with the exception of some drag brace struts). For this reason OO-ALC testing has been carried out using scrap A-10 landing gear inner cylinders. The A-10 landing gear was chosen since scrap items are readily available and A-10 gear sometimes come in for overhaul with obvious bending damage. Bend tests were performed on a rig set up at the University of Pennsylvania. The test rig is shown in Figure 4-4, with a specimen under stress. Even though this arrangement is designed to mimic service conditions Hill considers it a worst-case scenario since the cylinder is held in bushings in rigid blocks attached to a rigid bar. It has none of the flexibility provided by an actual landing gear assembly, which tends to spread the stresses between components. All tests were also made at full extension, whereas in actual landings the extension varies. This has the effect of concentrating the maximum bending stress and bushing line load at a single point in the test, rather than spreading them over a region of the inner cylinder as in an actual landing gear.

All coating was done at OO-ALC using a TAFA JP5000 HVOF gun and optimized deposition conditions. The spalling thresholds for 0.010"-thick WC-Co coatings are shown in Figure 4-5. Most tests were carried out at R= -0.33, which the Air Force calculates is their expected R ratio for deflection and spring back. Only the brown point was taken at R= -1. Testing was done in a series of steps of increasing strain, using 50 cycles per step to 190 ksi, and 10 cycles per step thereafter until coating failure. The force at the outer end of the bushing at the top of the bar was computed by the standard equation for the maximum stress at the outer fiber of a beam:

$\sigma_{\max} = \frac{Mc}{I}$, where M is the moment, c the radius, and I the moment of inertia.

All data were taken while recording strain with a strain gauge. Even given the complexity and size of the system, the failure stress/strain points fell close to the expected elastic Mc/I curve. (In fact, as expected, they actually fell somewhat to the left of the Mc/I curve due to the small but finite contribution of the high modulus coating to

the stiffness of the tube.) Since a structural engineer would not include the coating contribution in stress and strain calculations, in Figure 4-5 the contribution of the coating to the modulus is removed and these points are displayed on the Mc/I line. The stresses for these points can be read from the vertical axis, while the corresponding strains are indicated by the positions of the equivalent color points on the lower horizontal axis. The stress/strain curve computed by finite element analysis for this test cylinder, as well as the standard reference stress/strain curve (applicable to axial stress) are also shown on the graph. Note that all the R= -0.33 data lie above the yield point of the steel indicated by the 0.2% offset dashed line.

It is important to note that under tensile stress 300M steel would broadly follow the black reference curve of Figure 4-5. At lower stress the bending and tensile stress/strain curves approach each other, but diverge strongly above yield. Clearly, under tensile stress in a stress-controlled test rig (such as those used by HCAT/Metcut and NAVAIR) the strains equivalent to these same stresses are larger, and increase rapidly as the curves diverge. Therefore we would expect to see failures at lower axial stress than bending stress once the proportionality limit is exceeded.

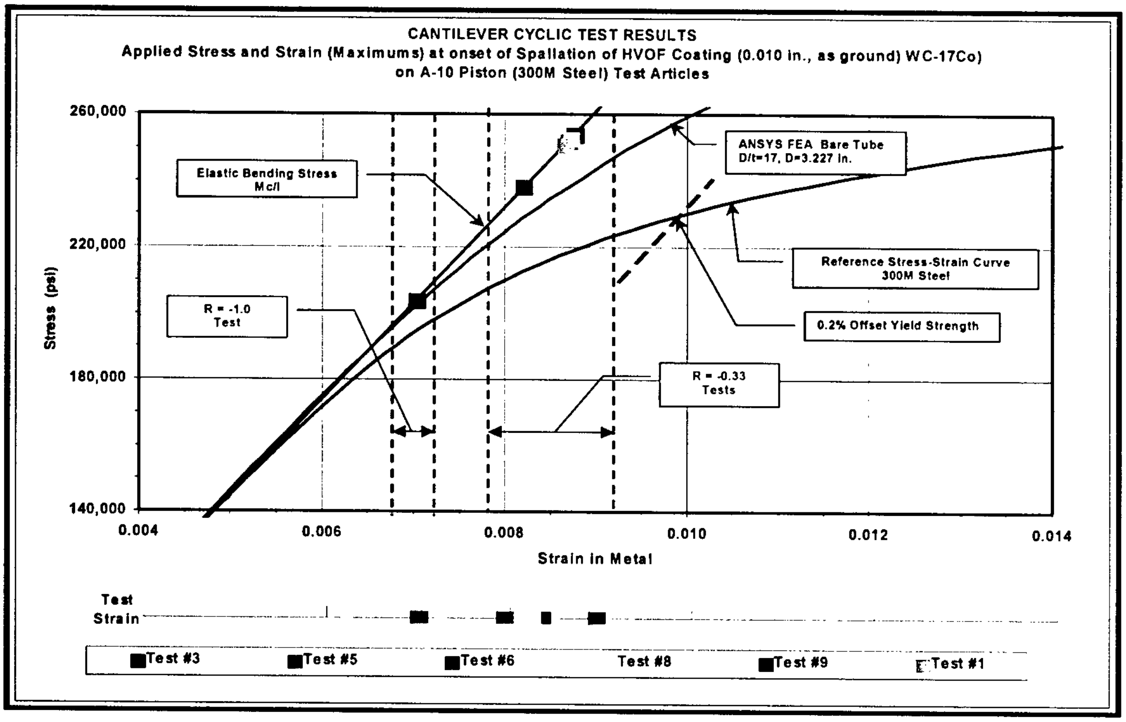


Figure 4-5. Bend Test Spalling for A-10 Landing Gear Cylinder Under Strain Control (0.010"-thick WC-Co, R= -0.33) (OO-ALC)

The delamination seen in these tests takes place over a wide area in the region of maximum strain and is accompanied by an array of circumferential cracks (visible with FPI) where the strain in the coating exceeds its strain-to-failure. This is shown for a 0.015" coating in Figure 4-6, where the brown mark in the center of the field of view is the location of the bushing. Outside the bushing, in the area of maximum tensile strain, the coating has completely delaminated. (This does not happen in the maximum compressive strain area 180° around the tube.) The area within the bushing shows some delamination and peeling. A view of the same area under FPI clearly shows the crack array (Figure 4-7). Note that the cracks are only found on the maximum tensile stress side of the tube and do not extend below the centerline.

Figure 4-6. Spallation of a 0.015"-thick WC/CoCr Coating from a Test Cylinder (OO-ALC)

On the basis of their testing OO-ALC have concluded that spalling is not likely to be a serious issue for Air Force aircraft, and have begun to qualify components for HVOF overhaul, starting with the lowest-risk items. Twelve different items are qualified as of the time of writing.

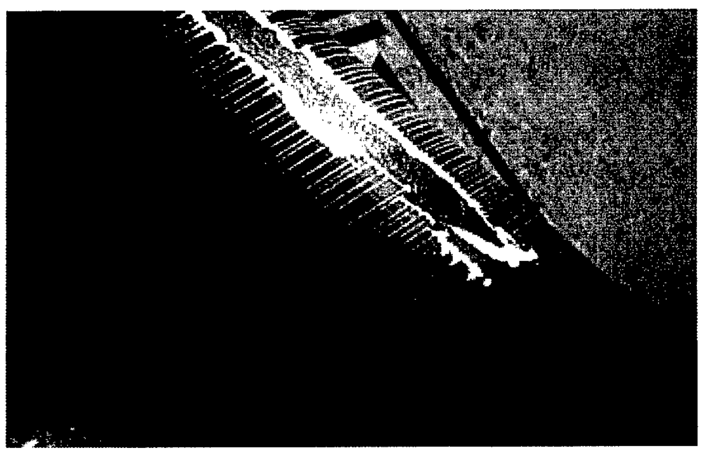


Figure 4-7. Same as Figure 4-6 , But Under FPI

4.3. References

4.1 Jean-Gabriel Legoux, National Research Council Canada, 22nd HCAT Program Review, San Diego, CA, April 2003 (available at www.hcat.org)

4.2 Eui Lee, Naval Air Systems Command, 22nd HCAT Program Review, San Diego, CA, April 2003 (available at www.hcat.org)

4.3 Craig Edwards, Hill Air Force Base, 22nd HCAT Program Review, San Diego, CA, April 2003 (available at www.hcat.org)

5. Component Rig and Flight Testing

5.1. Rig Testing

5.1.1. F/A-18 E/F Main Landing Gear Pins

In 1999, Boeing St. Louis conducted a full-scale fatigue test, designated FT66, on the left-hand main landing gear (MLG) from the F/A-18 E/F aircraft. The FT66 assembly included a trunion, lever, axle, shock absorber, simulated side brace, retract actuator, and planing mechanism. The purpose of the fatigue test was to demonstrate, with a full-scale test article, that the re-designed MLG met the repeated load requirements of MIL-A-8867. The success criterion for the entire test was that selected gear components had to complete the simulated flight hours (SFH) presented in Table 5-1 without failure. Failure was defined as any deformation or crack that would require repair, replacement or inspection to maintain structural integrity. In addition to the SFH testing, some components were subjected to constant amplitude testing (CAC) as well. In general, the simulated flight hours plus the CAC represented two lifetimes for the MLG.

Table 5-1. F/A-18 E/F Main Landing Gear Fatigue Simulated Flight Hour Success Requirements

F/A-18E/F MAIN LANDING GEAR FATIGUE TEST
SIMULATED FLIGHT HOUR SUCCESS REQUIREMENTS

Part Number	Component	Location[1]	Qualifying SFH	Qualification Inspection SFH[2][3]
74A400961	Trunnion	Gusset	14000	14000
		O/B Knee Joint Lug	9300	14000
		Flower Pot	9900	14000
		Forward Attach	14000 & C.A.C	14000 & C.A.C
		Tie Down Lugs	13000	14000
74A400901	Lever	Drain Hole	12900	14000
		O/B Lug Root	12000	14000
		O/B Lug Lube Hole	9500	14000
74A400941	Axle	Polygon	14000 & C.A.C	14000 & C.A.C
		A1	4900	8000
		Section CC	12900	13000
		Brake Flange	14000 & C.A.C	14000 & C.A.C
74A400504	Knee Pin	Head Relief	12700	14000
74A400735	Side Brace Universal	Thread Relief	7700	8000
74A400951	Crank	Lock Link Attach Lug	14000 & C.A.C	14000 & C.A.C
74A400512 74A400536 74A400538	Lower Lock Link Upper Lock Link Lock Link Yoke	Lock Link Load Path	14000 & C.A.C	14000 & C.A.C

Prior to initiation of this test, there was an opportunity to include some attach bolts and pins that are normally coated with electrolytic hard chrome but which were instead

coated with HVOF WC/Co. These were:

1. Upper oleo pin, part number 74A400645-7001
2. Side brace to universal attach pin, part number 74A400748-2001
3. Upper side brace attach pin, part number 74A400527-7001

These components were not considered to actually be a part of the formal test and their failure would not have been considered a FT66 test article failure. Thus, this provided an excellent opportunity to assess the performance of the HVOF WC/Co coatings without increasing the risk to the entire test program.

Initially the EHC plate was stripped from one each of the components and then WC/17Co coatings were applied in accordance with Boeing specification BAC 5851, Class 2, Type I using a Sulzer-Metco Diamondjet hybrid gun with hydrogen as the fuel gas and Diamalloy 2005 powder. Air cooling was used to ensure that the surface temperature of the components did not exceed 350° F during coating deposition. The coatings were deposited to a thickness of 0.006" and were then ground to a final thickness of 0.004" and surface finish of 8 (+0/-2) microinches Ra using low-stress grinding techniques.

Figure 5-1. shows the location of the WC/Co-coated components in the MLG. For the actual test procedure, the MLG was cycled in 1000 SFH blocks to the total of 14,000 SFH. During testing, general walk-around visual inspections were conducted at 500 SFH block intervals. Major non-destructive inspections were conducted at least every 2000 SFH, beginning at 8000 SFH.

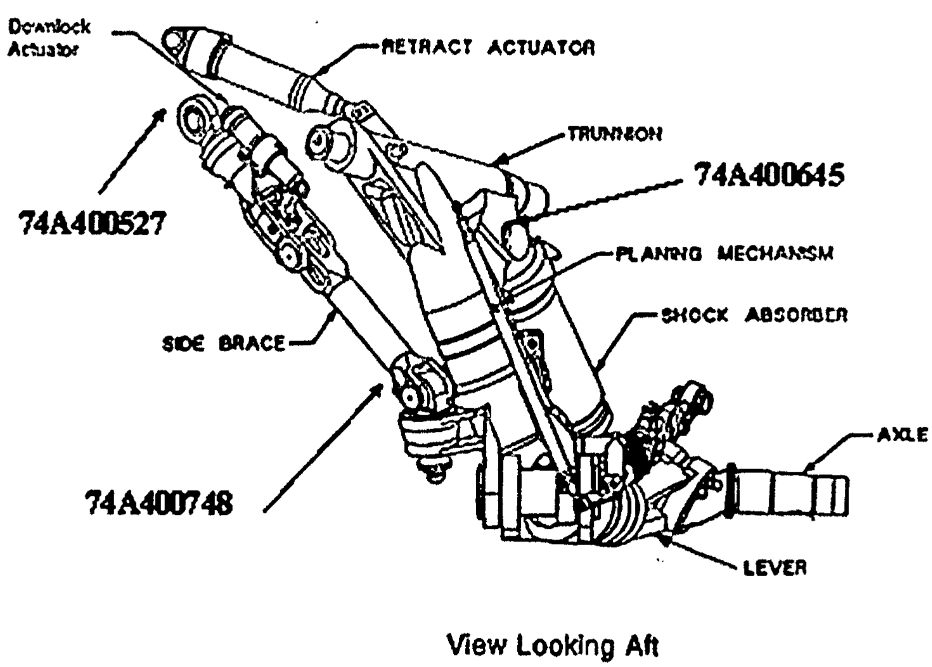
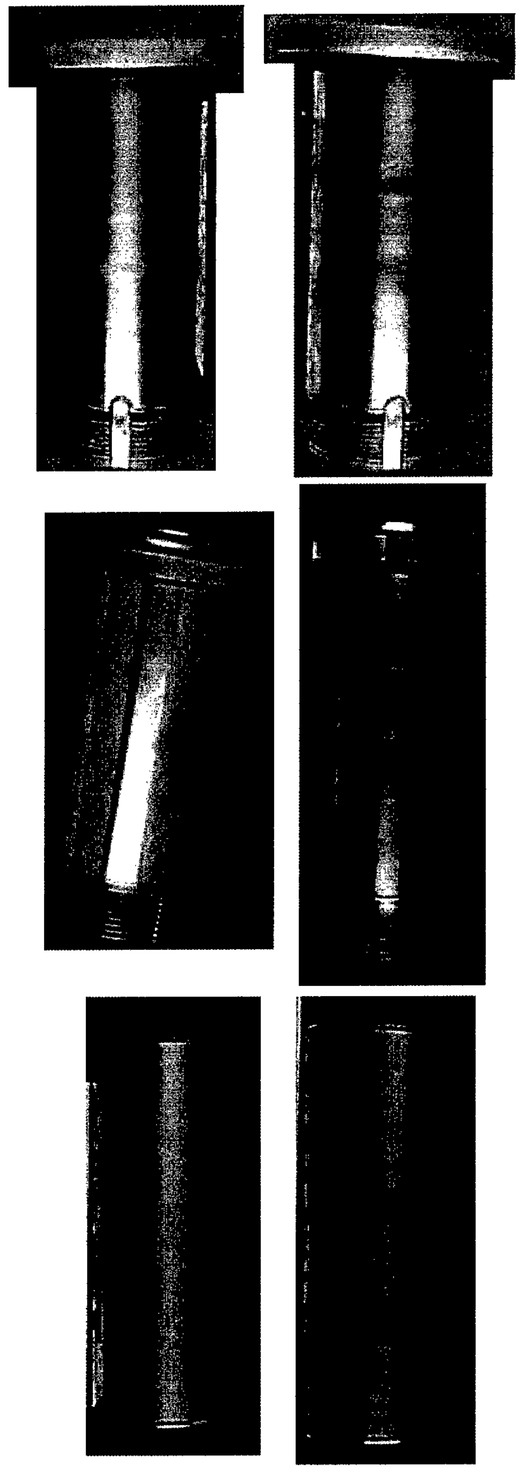


Figure 5-1. Location of HVOF-coated Pins in Boeing F/A-18E/F Main Landing Gear Fatigue Test

At the end of spectrum testing the HVOF coated pins showed only some darkening and staining, but no coating damage and no measurable wear. At the end of the CAC test the results were the same, except that there had been some material transfer from the Cu-Be bushings onto the HVOF surfaces. The three pins are shown at the ends of these two tests in Figure 5-2..

The conclusion of the testing was that the performance of the HVOF-coated pins was at least as good as that of EHC-coated pins, and that they "passed" the test. Boeing would require more testing to qualify the coating for other components in the landing gear such as the piston and axle journals.



74A400645
Oleo Attach
Pin

74A40052
7 Upper
Sidebrace
Attach Pin

74A400748
Lower
Sidebrace
Attach Pin

Figure 5-2. HVOF WC/Co-coated Pins Used in Boeing F/A-18E/F MLG Rig Test (Left, end of 14,000 hr spectrum test; right, end of CAC test (Boeing St Louis))

5.1.2. P-3C Main Landing Gear Piston

The four-engine turboprop P-3C was first introduced into the Navy fleet in 1968. Currently, the Navy operates 237 P-3C aircraft around the globe generally for anti-submarine warfare, search and rescue, mining and anti-surface warfare, and over-land intelligence, surveillance and reconnaissance. The Navy and its Foreign Military Sales partners initiated the P-3C Service Life Assessment Program (SLAP) to re-assess the P-3C fatigue life in 1997. This program also determines structural inspections, modifications, replacements and redesigns necessary to extend the P-3C operational service life to meet inventory requirements through at least the year 2015.

Phase II of the SLAP included the design of structural parts/assemblies to be included in Service Life Extension Program (SLEP) modification kits, development of a test spectra representative of projected P-3C Navy fleet usage, and testing of a P-3C aircraft containing the SLEP modification kits to the equivalent of two times the desired service life as a minimum. Lockheed-Martin was selected as the prime contractor for performance of the testing under the SLAP program. The total fatigue life capability of the P-3C aircraft was demonstrated using a production fleet aircraft. The test article consisted of the fuselage, wing, empennage, nose landing gear (NLG), main landing gear (MLG), engine nacelles and control surfaces. The test duration, which included all aging and testing cycles, was based on total accumulated fatigue damage from all loading sources rather than just from the Fatigue Test Spectrum Hours (FTSH) alone. The testing was intended to simulate the ultimate planned service life of the P-3C as follows:

Flight hours:	30,000
Number of flights:	8,802
Total Landings:	47,154
Intermediate full-stop landings	8,599
Final full-stop landings	8,802
Touch-and-go landings	29,753

It was decided that as part of the test, the piston on the left-hand MLG would be coated with HVOF WC/17Co instead of EHC. A piston was shipped to Naval Aviation Depot Jacksonville where the hard chrome was removed using standard stripping techniques. Then the piston was sent to Southwest Aeroservice where it was grit blasted and WC/17Co coatings were applied in accordance with Boeing specification BAC 5851, Class 2, Type I using a Sulzer-Metco Diamondjet hybrid gun with Diamalloy 2005 powder and with hydrogen as the fuel gas. Air cooling was used to ensure that the surface temperature of the components did not exceed 350° F during coating deposition. The coatings were deposited to a thickness of 0.006" and were then ground to a final thickness of 0.003" and surface finish of 8 (+0/-2) microinches Ra using low-stress grinding techniques. Figure 5-3. shows the MLG piston during application of the WC/17Co.

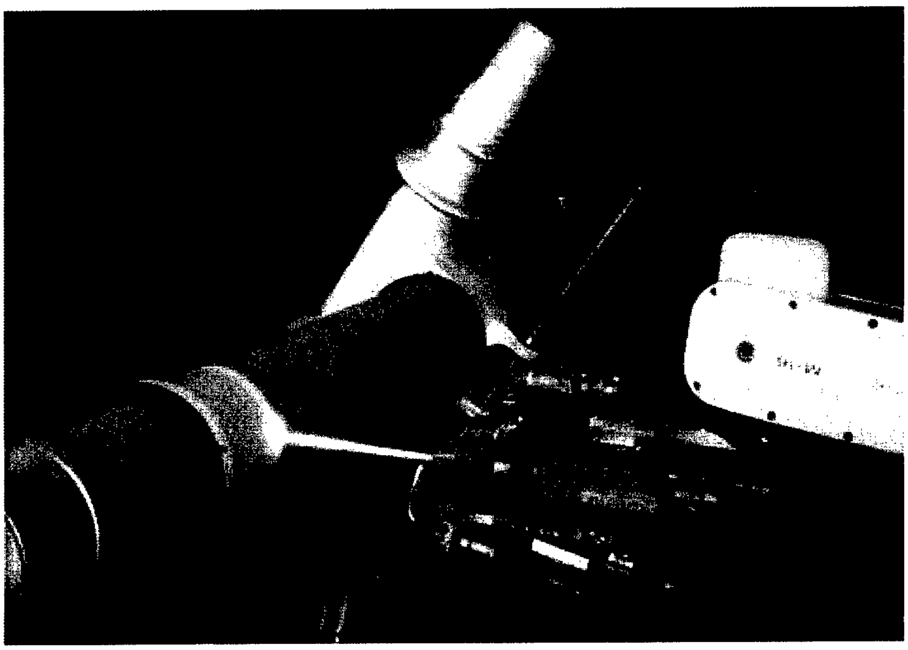


Figure 5-3. Application of HVOF WC/17Co Coating to P-3C MLG Piston

Following processing the piston was delivered to Lockheed-Martin in Marietta, Georgia where it was assembled into the left-hand MLG which then was mounted onto the test article as shown in Figure 5-4. and Figure 5-5..

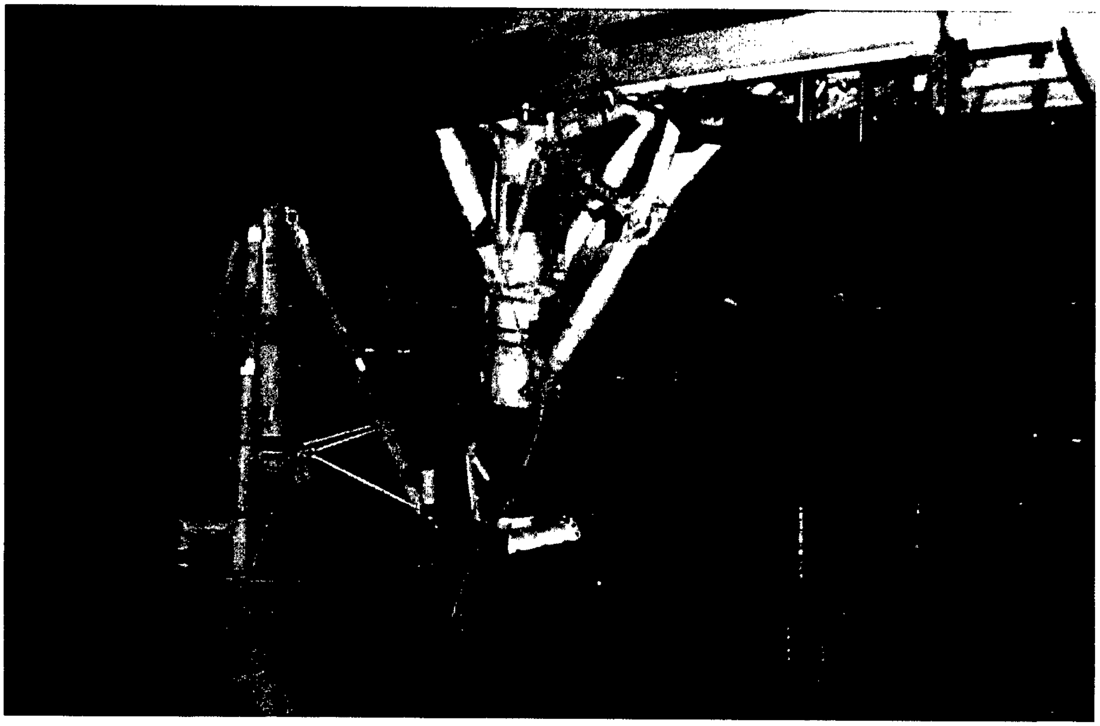


Figure 5-4. Left-hand MLG Containing HVOF WC/17Co-coated Piston Mounted on P-3C Test Article at Lockheed-Martin in Marietta, Georgia

The test was initiated in August 2001 and was suspended in April 2002 to perform repairs on some of the equipment that was applying the loads to the structure. The test was resumed in September 2002 and concluded in March 2003. The test was extended to a total of 38,000 simulated flight hours (SFH), with approximately 250,000 cycles on the MLG representing 47,000 landings (equivalent to two fatigue lifetimes).

Following the test, the WC/17Co-coated piston was visually inspected with no evidence of any coating cracking or delamination. Fluorescent penetrant inspection of the WC/Co coating also showed no evidence of coating cracking or other type of deterioration.

The conclusion was that the WC/Co coating successfully completed the full-scale fatigue test and therefore is qualified for use on operational aircraft.

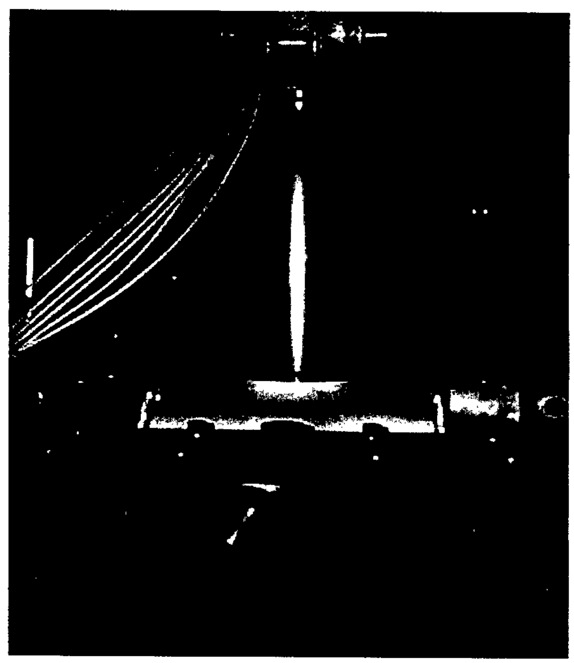


Figure 5-5. Close-up of HVOF WC/17Co-coated Piston in MLG

5.2. Flight Testing

5.2.1. E-6A Uplock Hook Shaft

The E-6A is a Navy reconnaissance aircraft similar to the Boeing 707 (see Figure 5-6.). In February 1999 Naval Aviation Depot Jacksonville arranged through the E-6A program office to have two uplock hook shafts from the main landing gear coated with HVOF WC/17Co and installed on an aircraft operating out of Tinker Air Force Base. NADEP Jacksonville obtained two of the shafts and stripped the EHC coating from the journal areas. Then the components were shipped to Hitemco where the areas to be coated were grit blasted and then WC/17Co coatings were applied in accordance with Boeing specification BAC 5851, Class 2, Type I using a Sulzer-Metco Diamondjet hybrid gun with Diamalloy 2005 powder and with hydrogen as the fuel gas. Air cooling was used to ensure that the surface temperature of the components did not exceed 350^{o} F during coating deposition. The coatings were deposited to a thickness of 0.008" and were then ground to a final thickness of 0.005" and surface finish of 8 (+0/-2) microinches Ra using low-stress grinding techniques. Figure 5-7. shows one of the uplock hook shafts following application of the WC/Co coating.

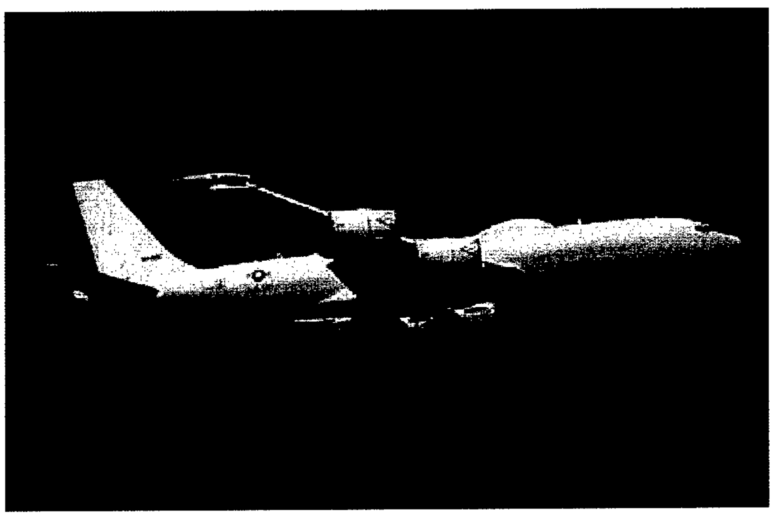


Figure 5-6. Navy E-6A Reconnaissance Aircraft

Two WC/17Co-coated uplock hook shafts were installed on Aircraft 164388 in March 1999 and immediately commenced operations at Tinker AFB. A third uplock hook shaft was installed on Aircraft 162784 in February 2000. Periodic inspections of the shafts were conducted. As of 28 February 2003, Aircraft 164388 had 3446 flight hours and 2731 landings, and Aircraft 162784 had 3871 flight hours and 2756 landings. Inspections of the components indicated that there was no evidence of wear, delamination, cracking or other type of degradation of the WC/Co coatings. They are continuing in service.

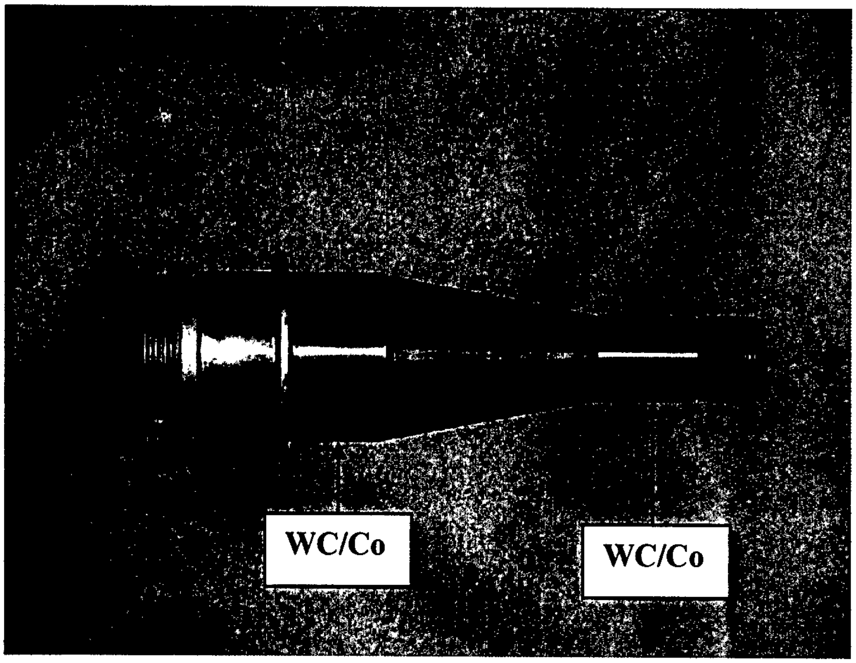


Figure 5-7. E-6A Uplock Hook Shaft

5.2.2. P-3C Main Landing Gear Components

In early 1999, Naval Aviation Depot Jacksonville obtained approval from NAVAIR to conduct flight testing of HVOF coatings on a P-3C landing gear. NADEP Jacksonville obtained a MLG Piston Assembly (Part Number 901022-1, Serial Number 703) and stripped the EHC coating from the piston cylinder and axle journals. Then the assembly was shipped to Hitemco where the areas to be coated were grit blasted and then WC/17Co coatings were applied in accordance with Boeing specification BAC 5851, Class 2, Type I using a Sulzer-Metco Diamondjet hybrid gun with Diamalloy 2005 powder and with hydrogen as the fuel gas. Air cooling was used to ensure that the surface temperature of the components did not exceed 350° F during coating deposition. The coatings were deposited to a thickness of 0.008" and were then ground to a final thickness of 0.004"-0.005" and surface finish of 8 (+0/-2) microinches Ra using low-stress grinding techniques.

The piston assembly was returned to NADEP Jacksonville where it was installed on Aircraft Number 156522. The aircraft completed overhaul in December 1999 and was returned to Squadron VP-30 operating out of Jacksonville Naval Air Station. Figure 5-8. shows the landing gear and the WC/Co-coated area of the piston. The coated axle journals cannot be seen since they are obscured by the wheels.

Figure 5-8. P-3C Main Landing Gear with HVOF WC/17Co-coated Piston Cylinder (indicated) and Axle Journals

The Navy P-3 Flight Support Team (FST) issued a Maintenance Engineering Advisory message to VP-30 indicating that this was a special test article. The P-3 FST and NADEP Jacksonville Material Engineering Laboratory coordinated periodic inspections in conjunction with normal squadron inspection intervals (normally 224 days) to monitor and record the performance of the WC/Co coating. Inspections were both visual and fluorescent penetrant. In August 2000 the component had been subjected to 850 landings and it was removed from service due to an internal oil leak not related to the WC/Co coating. The component was repaired, returned to VP-30, and installed on Aircraft 160284 in April 2001. As of 29 March 2003 the component had been subjected to a total of 2133 landings combined on both aircraft. Visual and fluorescent penetrant inspection indicated no evidence of coating wear, delamination, cracking, corrosion, or other type of degradation of the WC/Co coatings. The landing gear is continuing in service.

6. Producibility

6.1. Stripping of HVOF coatings

Stripping is a very important process for depot overhaul, since old coatings must be removed in order to rebuild worn or damaged components. Although any coating can of course be ground off, chemical stripping is generally preferred since it does not remove base material and since it minimizes limited personnel resources. Stripping of WC/Co and WC/CoCr takes place through dissolution of the matrix metal, which liberates the carbides.

Several sets of tests have demonstrated the efficacy of the environmentally benign Rochelle salt stripping solution for both WC/Co and WC/CoCr.

6.1.1. Stripping of HVOF WC/Co – Sacramento ALC, NADEP Cherry Point

This work was done under AF Contract F04699-98-C-0002 CLIN 1 AY, and was headed by Elwin Jang of SM-ALC and Robert Kestler of NADEP Cherry Point, who authored the following report.

Preparation of Test Specimens: Each specimen was engraved with a unique laboratory number.

- Steel panel, AISI 1010, size 0.060" x 3.0" x 5", 12 each
- Steel rod, solid, Type 4340, size 5/8" diameter x 5"L, 1 each
- Stainless steel rod, solid, Type PH13-8Mo, size 0.9 1.0" diameter x 5- 6"L, 1 each

Southwest Aeroservices in Tulsa, OK applied both HVOF coatings, using a Jet-Kote II spray-coating system equipped with robotic arm and hydrogen fuel.

The coating materials were H.C. Starck's Amperit 526 (WC-Co, 83/17) and Praxair's AI-1186 (WC-Co-Cr, 86/10/4). The vendor product descriptions and QC test results are summarized in Table 6-1. The coating thickness of each panel is tabulated in Table 6-2. The vendor subsequently aged the coated panels by shot peening to 0.008"-0.012" thickness, 200% coverage, using MIL Standard 330 high hard shot.

Table 6-1. Vendor WC-Co and WC-Co-Cr Coatings QC Test Results

Requirements	Units	Control Limit	WC-Co	WC-Co-Cr
Visual inspection	N/A	No cracks, blisters, lumps, splatter, chipping, flaking, or discoloration allowed	No cracks, blisters, lumps, splatter, chipping, flaking, discoloration	No cracks, blisters, lumps, splatter, chipping, flaking, or discoloration
Part temperature	Deg F	<350	<350	<350
Substrates preheat temp.	Deg F	As required	Remove moisture	Remove moisture
Powder composition	Wt. %		Co 15-18, C 4.9-5.3, Fe <0.2	Co 10, Cr 4, C 3.25-3.9, Fe 0.7-0.8
Powder manufacturing method	N/A		Agglomerated & sintered	Sintered & crushed
Powder size range	Micron	10-53	10-53	10-53
Macrohardness (superficial hardness)	Rc	>55	94.6, avg. of 10	95, avg. of 10
Microhardness	DPH_{300}	>1000	1171, avg. of 10	1225, avg. of 10
Tensile bond strength	PSI	>10,000	>13,254, avg. of 5	>12,933, avg. of 5
Bend test	N/A	No separation between coating & substrate	No separation between coating & substrate	No separation between coating & substrate
Oxide content	Vol. %	<1	<1	<1
Roughness (as-sprayed)	Microinch Ra	150-250	111	150
Porosity (void volume)	Vol. %	<1	<1	<1
Microstructural uniformity, 200x field	Unmelted particle	<3	0	0

Table 6-2. Coating Thickness of Panels

Specimen Number	Coating	Initial Coating Thickness, x 0.001"
1	WC-Co	4.86
2	WC-Co	5.00
3	WC-Co	5.16
Avg. of 1-3	WC-Co	5.00
5	WC-Co	11.50
6	WC-Co	8.37
7	WC-Co	8.60
Avg. of 5-7	WC-Co	9.49
9	WC-Co-Cr	3.70
10	WC-Co-Cr	3.50
11	WC-Co-Cr	4.10
Avg. of 9-11	WC-Co-Cr	3.76
13	WC-Co-Cr	8.13
14	WC-Co-Cr	8.26
15	WC-Co-Cr	8.04
Avg. of 13-15	WC-Co-Cr	8.14

Note: Panels #4, #8, #12 were used for laboratory tests.

6.1.1.1.Masking, fixturing, and positioning specimens

Masking specimens. All four sides of the panels were masked off by a 1/8-inch band of Military Specification MIL-P-23377 epoxy primer to preclude possible solution entry from the panel edges into the coating and substrate interfaces. Two coats of primer were applied, air dried for over 72 hours, and baked at 325° - 330°F for 23 hours. The effective dimensions of the average exposed panel area were about 2.25" by 4.25", or about 9.56 square inches. Each specimen was stored in a sealed plastic bag.

Specimen fixturing. A titanium fixture for anodizing was used for positioning the panels because a stainless steel fixture was not available. The panels were fastened to the fixture with screws. Each panel was positioned horizontally and alternated at a 90° angle.

6.1.1.2.Process Solutions and Operating Conditions

Rochelle salts solution:

• Sodium carbonate:	20 – 30 oz/gal
• Sodium potassium tartrate (Rochelle salts):	8 – 12 oz/gal
• Deionized water:	Balance as needed
• pH:	11 – 12
• Operating temperature:	$130^{\circ} - 150^{\circ}F$
• Current:	40 – 80 A/ft^2 DC, anodic
• Voltage:	As required (~4 – 6 V DC)
• Tank dimensions:	48" x 48" x 48"
• Tank volume:	200 gallons

Note: This was a new solution.

Proprietary general purpose alkaline cleaner:

• Make-up	Proprietary (Oakite)
• Operating temperature:	$130^{\circ} - 150^{\circ}F$
• Tank dimensions:	48" x 48" x 48"
• Tank volume:	200 gallons

6.1.1.3.Stripping Process Used and Specimen Measurements Conducted

The test procedure was as follows:

1. Weigh each coated panel to 0.1 gram and measure the panel thickness to 0.1 mil at three points (1" from top, middle, and 1" from bottom) near the edges with a micrometer. (Note: The measuring accuracy was about 0.0002"-0.0005")
2. Fasten the panels numerically from the top of the fixture with the coating side up and in parallel.
3. Immerse the fixture in the hot alkaline cleaner for 5 minutes.
4. Immerse the fixture in a cold water rinse tank for 5 minutes.

Run 1:

1. Immerse in the Rochelle salt solution tank maintained at $150^{\circ}F$ at potential of 6 volts and electrolytically strip for one hour. (Note: Since the titanium fixture was a poor electrical conductor, the current density was about 20-25 A/ft^2 which was below the 40-80 A/ft^2 requirement. Therefore, the stripping rate was relatively slow.)
2. Remove the fixture from the process solution tank. Rinse in two different cold water tanks for 5 minutes in each tank. Rinse in a hot water tank ($140^{\circ}F$) for 5 minutes. Blow dry with filtered compressed air.
3. Remove panels #2 (WC-Co, 0.005"-thick) and #6 (WC-Co, 0.0084"-thick) from the fixture to inspect and weigh. (Note: Inspection revealed that more coating

was removed near the sides than in the center, apparently due to higher current density near the edges. There was discoloration or a very thin smudge film deposited on the panel surfaces. The epoxy maskant appeared to be intact.)

Run 2, 3 and 4:

1. Immerse the fixture in the Rochelle salt tank for 1.5 hours at a potential of 9 volts, to generate a current density of about 40 A/ft2.
2. Repeat 2 above. Remove all panels from the fixture. Inspect panel surfaces, measure panel thickness and weigh.

6.1.1.4.Stripping test measurements

Table 6-3. Percent Coating Thickness Removal

Specimen No.	Coating/Avg. Mils	% Thickness Removed After 2.5 Hr.	% Thickness Removed After 4.0 Hr.	% Thickness Removed After 5.5 Hr.
1	WC-Co	Not available	91.8	~100
2	WC-Co	94.6	~100	~100
3	WC-Co	81.4	96.9	~100
Avg. 1-3	WC-Co/5.00	88.0	96.2	~100
5	WC-Co	78.0	<100	<100
6	WC-Co	78.5	<100	<100
7	WC-Co	65.5	87.6	<100
Avg. 5-7	WC-Co/9.49	74.4	98.4	<100
9	WC-Co-Cr	91.9	99.2	~100
10	WC-Co-Cr	96.3	~100	~100
11	WC-Co-Cr	81.2	95.1	~100
Avg. 9-11	WC-Co-Cr/3.76	89.6	98.9	~100
13	WC-Co-Cr	50.4	94.7	<100
14	WC-Co-Cr	62.1	99.6	<100
15	WC-Co-Cr	87.1	89.2	<100
Avg. 13-15	WC-Co-Cr/8.14	66.5	94.6	<100

The coating areas around the edges of the panels were stripped faster than the central area, presumably because of higher current density around the edges (edge effects). Since the thickness was only measured at three locations at one edge in each panel using a micrometer, the stripping rate was characteristic of one edge, rather than the entire

panel. At the completion of the last run, there was almost no coating remaining on the thinly coated panels: panels #1-#3 and #9-11. There were some paint residue remaining on the thickly coated panels: #5-#7 and #13-#15. It did not appear that the minor stains or smudges on the coating surfaces would have impeded the stripping rate. The epoxy primer maskant was in good condition with minor amounts flaked off.

The thickness measurements in Table 6-3 and the weight measurements in Table 6-4 indicate that the stripping rates of WC-Co and WC-Co-Cr coatings are quite similar. Almost all of the coatings were stripped from all panels after four hours. In the last column of Table 6-3 and Table 6-4, "~100%" means practically no coating residue left on the panel; whereas, "<100%" means small amounts of coating residue remained near the center of the panel.

Table 6-4. Percent Coating Weight Removal

Specimen Number	Coating	% Wt. Removal After 1.0 Hr.	% Wt. Removal After 2.5 Hr.	% Wt. Removal After 4.0 Hr.	% Wt. Removal After 5.5 Hr.
1	WC-Co		92.85	98.57	~100
2	WC-Co	29.28	92.14	97.86	~100
3	WC-Co		91.49	97.87	~100
Avg. 1-3	WC-Co		92.16	98.10	~100
5	WC-Co		55.07	84.06	<100
6	WC-Co	20.19	53.99	82.63	<100
7	WC-Co		67.06	99.22	<100
Avg. 5-7	WC-Co		58.71	88.64	<100
9	WC-Co-Cr		95.92	98.98	~100
10	WC-Co-Cr		94.95	97.98	~100
11	WC-Co-Cr		97.06	99.02	~100
Avg. 9-11	WC-Co-Cr		95.98	98.66	~100
13	WC-Co-Cr		62.32	86.51	<100
14	WC-Co-Cr		86.42	98.64	<100
15	WC-Co-Cr		83.48	98.21	<100
Avg. 13-15	WC-Co-Cr		77.41	94.45	<100

The data are summarized in Figure 6-1

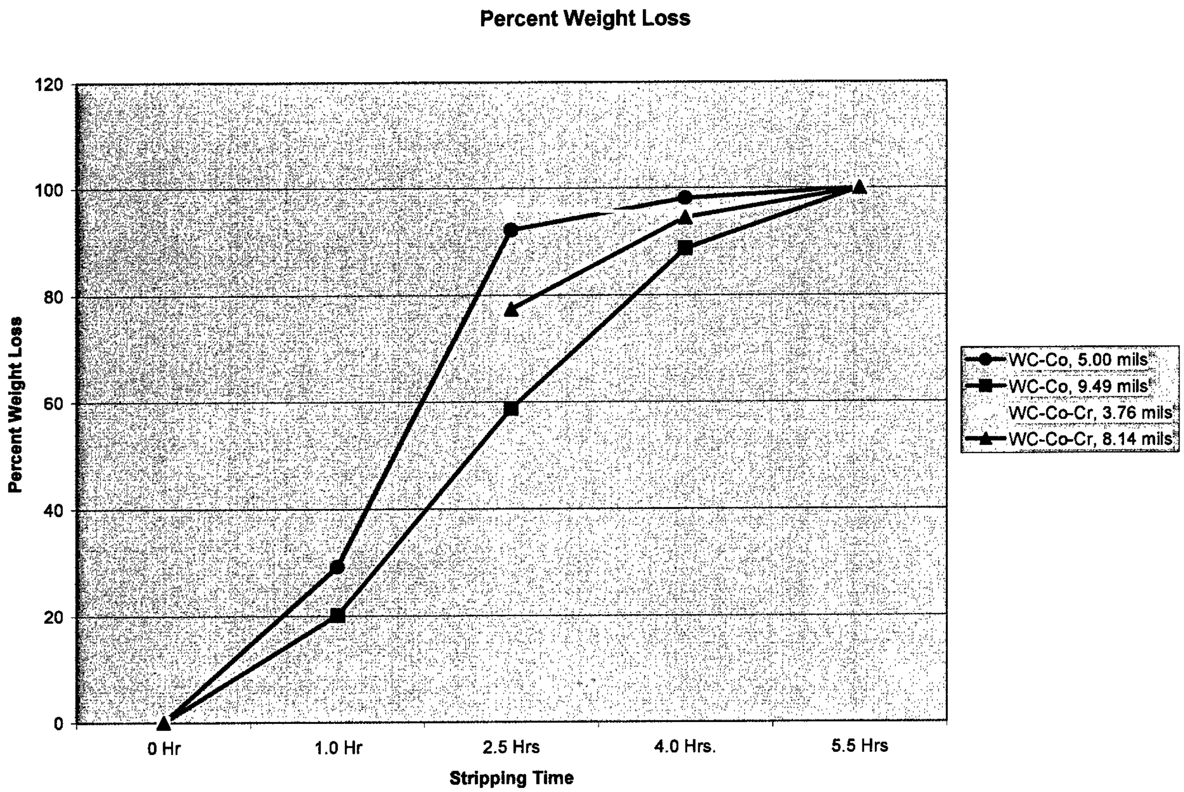


Figure 6-1. Weight Loss as a Function of Stripping Time

6.1.1.5.Post Stripping Inspections and Cross-Sectional Examination

Visual Inspection: The coatings on the thinly coated panels, #1-#3 and #9-#11, were completely stripped. The thickly coated panels, #5-#7 and #13-#15, had some coating residue on central areas.

The bare sides of the panels showed stains and rust, apparently caused by handling, and immersion in alkaline solution and stripping solution. The epoxy primer maskant was mostly intact with minor chipping.

Microscopic Inspection: After stripping the panels showed staining but no etching.

6.1.1.6.Conclusions and Recommendations

Proposed chemical or electrochemical stripping acceptance criteria for HVOF coatings is as follows:

- Achieve a stripping rate of at least 0.001" per hour.
- Does not etch or deplete the substrate after subjecting to 10 hours of immersion or electrolytic etching. (The allowable amounts of etching or depletion are to be established based on future test results.)
- After subjecting the specimens to 10-hours of the stripping processing, they are

able to comply with the hydrogen embrittlement requirements of ASTM 519.

- The process solution does not contain known carcinogens or extremely toxic chemicals.
- A standard process in a conventional wastewater treatment plant can recycle the rinse water.

The Rochelle salt electrochemical stripping process for WC-Co and WC-Co-Cr coatings nearly complies with the above criteria. The substrate weight loss due to prolong etching was inconclusive. However, visual and microscopic (20X) examinations showed no evidence of depletion or pitting. The stripping rates for WC-Co and WC-Co-Cr coatings are comparable. The team recommended that a stripping test procedure and a stripping specification for production parts be developed for standardization.

Recommendations for future stripping tests:

- Use a stainless steel fixture to obtain higher current density in electrolytic stripping.
- Use rods as test specimens as most production parts are cylindrical. Because of non-uniform stripping due to edge effects use flat panels for stripping tests only if actual production parts to be HVOF-coated and stripped have flat surfaces.
- Allow the use of glass bead blasting for removing coating residue on parts.
- Use the same specimen substrates as the production parts (such as 4340 steel, PH13-8Mo stainless steel, and 7075 aluminum).
- Accurately weigh and measure all test specimens at the following times: before coating, after coating, at several intervals during stripping, and after stripping (when clean and dry). Take thickness measurements that represent the entire surface, near its centers, edges, and corners.
- Conduct tests to identify more effective maskants than Mil-P-23377 epoxy primer for use in electrochemical stripping. Determine suitable maskants for each stripping chemistry.
- Develop standards and procedures for aging coated specimens.
- Apply a thin film of corrosion protective oil to stripped low alloy steel parts to prevent rusting.

6.1.2. Stripping of HVOF WC/CoCr – Heroux Devtek, Canada

As part of their producibility testing for the Canadian HCAT, Heroux Devtek has tested various stripping solutions for WC/10Co4Cr on 4340 high strength steel. They measured dissolution rates with cyclic voltammetry Tafel curves, weight loss, and hydrogen embrittlement. Heroux checked several chemistries (Table 6-5). The S1 series were strippers commonly used for EHC and Ni, while the S2 series were strippers recommended for WC-Co.

Table 6-5. Stripping Solutions Tested by Heroux Devtek for HVOF WC/CoCr

Designation	Chemistry	Performance
S1-1	NaOH + Na_2CO_3 (Cr strip, MIL-STD-871)	Self-limiting
S1-2	NaOH (Cr stripping, MIL-STD-871)	Self-limiting
S1-3	Meta-nitrobenzane sulfonate + NaOH + Na cyanide (Ni strip, MIL-STD-871)	Works best, uniform, but ESOH concerns. Rate = 5.2 mils/hr
S2-1	Na_2CO_3 + sodium tartrate (Rochelle Salt), used for WC-Co stripping	Works well. Rate = 4.1 mils/hr
S2-2	Metal XB929 (commercial Ni strip)	Works well. Rate = 3.6 mils/hr

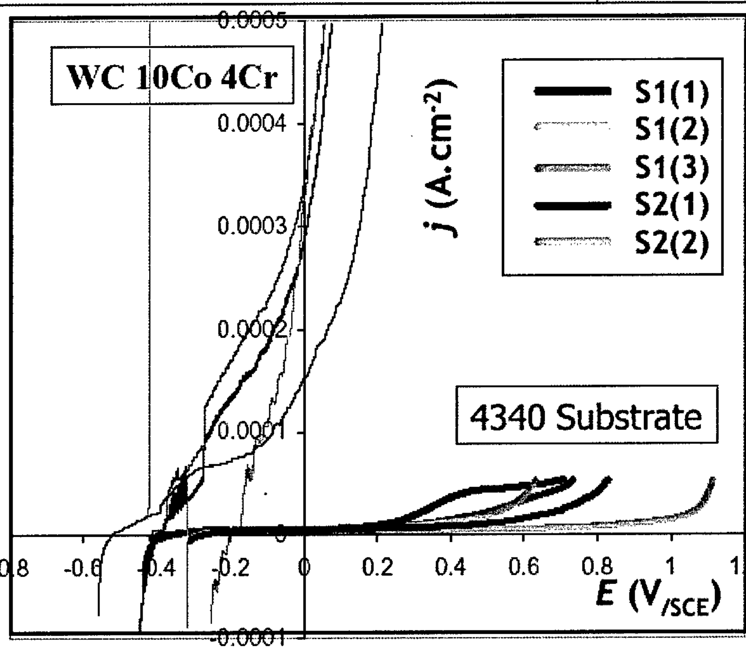


Figure 6-2. Polarization Curves for WC/CoCr and 4340 Substrate with the Stripping Solutions (Heroux Devtek)

Figure 6-2 shows that WC/CoCr coatings can be stripped at potentials at which the substrates are inactive, making it possible to strip the coating without substrate dissolution.

The solution that worked best, was the cyanide Ni stripper, type S1-3. It had the highest stripping rate and a uniform strip. This solution is often used for stripping Ni, but it has obvious ESOH issues.

Rochelle salt was found to work well (Figure 6-4), but the WC particles tended to be eliminated before the alloy matrix was dissolved. Note that the higher potential gave much more rapid stripping. Metal XB929 Ni stripper also worked well, but was slower than Rochelle salt (Figure 6-3).

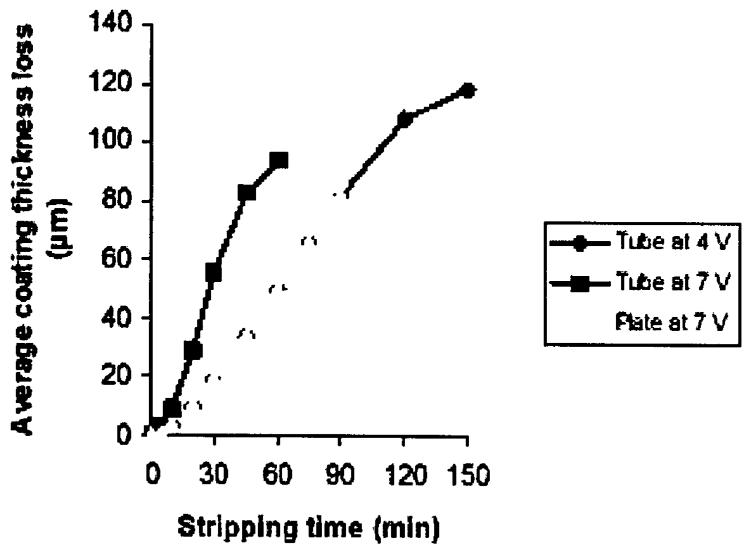


Figure 6-3. Stripping Rate of WC/CoCr by Type S2-2, Ni Stripper (Heroux Devtek)

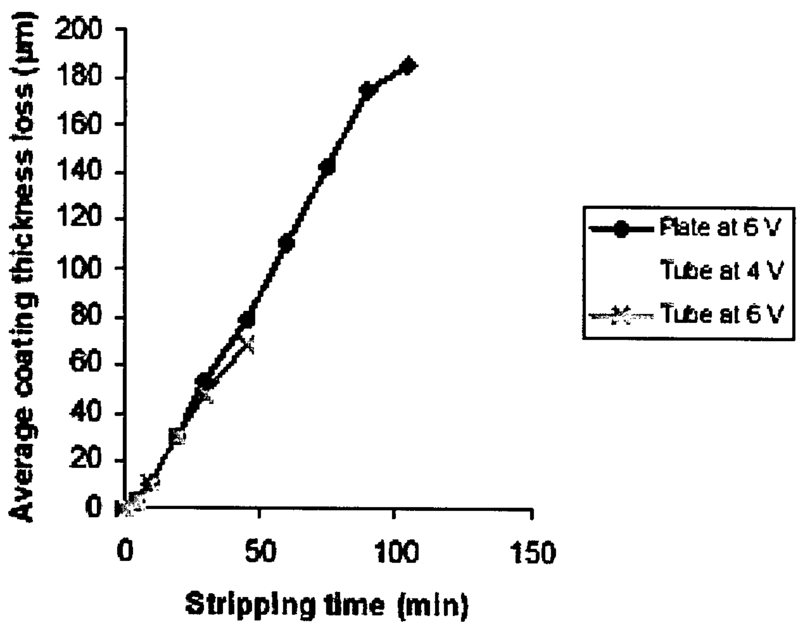


Figure 6-4. Stripping Rate of WC/CoCr by Type S2-1, Rochelle Salt Stripper (Heroux Devtek)

Ultrasonic agitation was found to greatly improve the stripping rate (Figure 6-5), presumably by removing stripped material (especially the carbide particles) from the surface. Ultrasonic agitators can be immersed in a standard stripping bath.

As we would expect from Figure 6-2, there was no hydrogen embrittlement since there was no dissolution of the substrate metal.

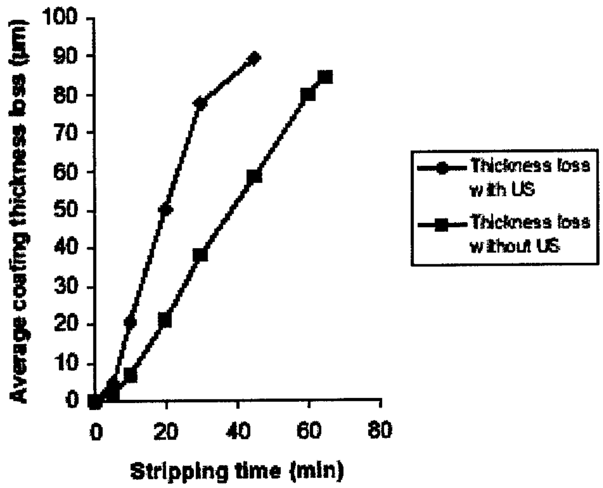


Figure 6-5. Effect of Ultrasonic Agitation (Type S1-3 Stripper)

6.2. Grinding

Grinding methods have been developed by Jon Deveraux of NADEP Jacksonville for HVOF carbide coatings, and these are the subject of an AMS specification currently in the approval process (see Section 8.4).

For grinding it is particularly important that the coating be ground efficiently with as little danger as possible of overheating (grind burning) the substrate steel. Grind burning is quite common with EHC and many manufacturers check for it as a matter of course with Barkhausen Noise (Rollscan) equipment. Prior qualitative history had suggested that it was difficult, but not impossible, to grind burn through an HVOF coating.

As part of their Canadian-HCAT work, Heroux Devtek carried out extensive grind testing [6.1]. They came to several important conclusions:

- Higher wheel speed (5000 to 7000 SFM) improves the finish.
- High work speed with low crossfeed improves the finish and decreases the total time of grinding, but optimum infeed is about 0.0002 in. Higher infeed decreases the finish and damages the coating.
- Lower grit number (larger abrasive particles) decreases productivity. Higher grit numbers obtain the same finish in a shorter time than lower ones.
- It is possible to grind burn the substrate when grinding the HVOF coating, although it is not as easy to do as with EHC.
- Abusive grinding is not necessarily evident to the naked eye. A finish that looks good to the eye can mask grind burns or coating damage.
- The best finish is obtained by grinding to a reasonable (but not very low) Ra and finishing with superfinish stone or tape. This typically gives a surface finish of <2µ" Ra and 95-99% bearing ratio, Tp. (Note that for hydraulics a Tp in the 60-

70% range may be preferred to better retain hydraulic fluid.)

6.3. Fluid compatibility

Heroux Devtek has assessed fluid compatibility through a combination of Tafel plots of dissolution rate, immersion test, and F-519 hydrogen embrittlement testing [6.2]. A wide range of production, overhaul, and service fluids were tested, with the results outlined in Table 6-6.

The only serious issues were possible hydrogen embrittlement effects from

- Oakite alkaline cleaning solution – a high dissolution rate was measured in Tafel plots for Oakite electrochemical cleaning. Embrittlement failure occurred after 54 – 148 hours (spec calls for >200 hours).
- Nital etch (used as a test for grind burns on steel after grinding and prior to coating) – Since by definition the solution etches and creates hydrogen, standard practice is to bake for 4 hours at 375°F. The 4 hour bake did not completely eliminate embrittlement failure, suggesting that hydrogen cannot migrate through HVOF WC/CoCr as readily as through EHC. A 12 hour bake did eliminate failure (Note: Slower hydrogen evolution through the HVOF coating in accord

Table 6-6. Fluid Compatibility of HVOF WC/CoCr (Heroux Devtek)

Fluid	Compatibility results
Organic materials	
Corrosion preventive products	No weight or finish change, no dissolution or embrittlement
Greases	No weight or finish change, no dissolution or embrittlement
Degreasers	No weight or finish change, no dissolution or embrittlement
Hydraulic fluids	No weight or finish change, no dissolution or embrittlement
Grease + hydraulic fluids	No weight or finish change, no dissolution or embrittlement
Aqueous solutions	
Cleaning solutions	No weight or finish change, no dissolution or embrittlement. Except: Oakite cleaning solution – Tafel plot shows 0.5 mil/hr dissolution rate after 5 min exposure; some embrittlement failures seen if not baked.
Inspection related products (FPI, MPI, nital etch)	No weight or finish change, no dissolution or embrittlement. Except: Nital etch – embrittlement failure if not baked or given standard 4 hr, 375°F bake. Heroux recommended 12hr bake.
Plating and stripping solutions	No weight or finish change, no dissolution or embrittlement

with the results of the HCAT embrittlement testing, see Section 3.7).

The only serious concern is with Nital etching, which is very commonly done to test for grind burns (the part is immersed, so nital etching to check one area exposes the entire part to the acid). If a much longer bake is required this will seriously impact the efficiency of the production or overhaul process, losing some of the efficiency gained through the use of HVOF coating. However, the nital etch sequence is as follows:

Cleaning in oakite → Immersion in nital → Rinse → Immersion in HCl → Rinse → Immersion in NaOH → Rinse. Since Oakite itself was found to cause embrittlement it is possible that the cleaning contributed to the hydrogen level and therefore to the time required for bakeout.

6.4. Non Destructive Inspection

6.4.1. Fluorescent penetrant inspection (FPI)

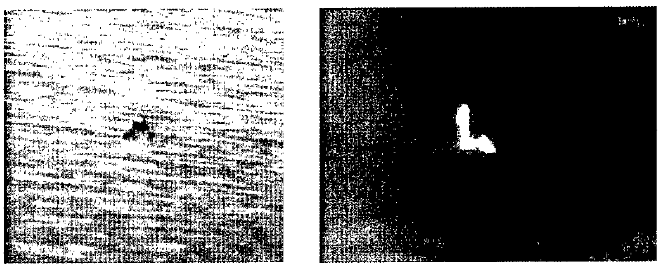


Figure 6-6. Damage Pit in HVOF WC/CoCr Coating (Left: standard; right: FPI)

The simplest method for observing cracks, pull outs, delamination, and other coating damage has been found to be fluorescent penetrant inspection (FPI). The major advantage of FPI is that all depots are set up for it and it permits rapid examination of large areas. Figure 6-6 shows that FPI can clearly bring

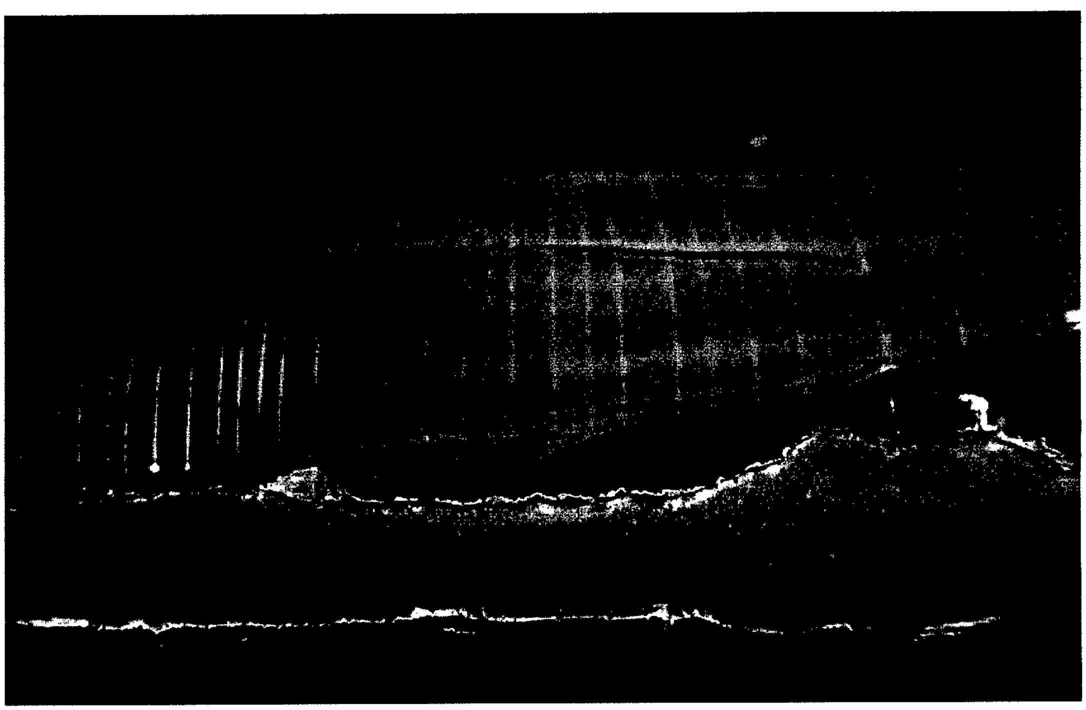


Figure 6-7. FPI of HVOF-coated Landing Gear After Fatigue to Stress Sufficient to Cause Coating Delamination, Showing Circumferential Coating Cracks (C. Edwards, OO-ALC)

out damage in a coated surface.

FPI is also capable of detecting cracks in the coated surface caused by high strain cycling. Figure 6-7 shows the surface of an A-10 landing gear piston coated with 0.015" WC/Co and cycled at 125 ksi [6.3]. FPI clearly shows both a major delamination and cracking of the coating.

6.4.2. Magnetic particle inspection (MPI)

MPI has been found to be not very useful for detection of cracks and damage in HVOF coatings (see Table 6-7).

6.4.3. Ultrasonic inspection

Ultrasonic inspection is not widely used in the depots as it is a specialized technique that is very slow when inspecting large areas.

Rupel and Pfeiffer of Boeing St Louis have tested several measurement methods for detection of cracks beneath HVOF and EHC coatings [6.4]: They made cracks in large tensile specimens by machining a starter notch, stressing to create a crack 0.25" long, and then machining off the starter notch and overcoating. The results of their evaluation of several detection methods are summarized in Table 6-7.

Table 6-7. NDI Testing of Substrate Cracks (Boeing St. Louis)

Test method	Results
Shear wave ultrasonic, 2.25MHz	Most consistent results. Able to easily detect through both 0.003" and 0.009" coatings
Surface wave ultrasonic, 2.25MHz	Easily detected through 0.003" coatings; marginal with 0.009" coatings
MPI	Unable to detect cracks even when propagated through coating
Eddy current	Marginal crack detection beneath coating; excellent detection when crack propagated through coating

The best method was ultrasonic flaw detection using shear waves. This method is geometry-dependent and worked equally well under hard chrome or HVOF. Surface wave ultrasonic detection was also able to detect the crack, but required far more gain for HVOF than for EHC. An example of the ultrasonic crack response is illustrated in Figure 6-8 for thin and thick HVOF coatings.

Bob Ware of AFRL has used an ultrasonic immersion pulse-echo technique to detect debonding prior to delamination in HVOF-coated tensile bars subjected to fatigue testing [6.5]. This approach is not easy, requiring immersion and automatic mapping of the returned ultrasonic pulse around the entire surface. It depends on using the signal strength of the echo from the back surface of the test item to determine the degree of delamination of the coating at the front, based on the principle that any debonded area will not transmit the ultrasonic pulse into the underlying steel. The method is capable of clearly detecting delamination before it can be seen visually. An example is shown in Figure 6-9, which shows that under the same high load fatigue conditions WC/CoCr delaminates at far fewer cycles than an equivalent WC/Co coating.

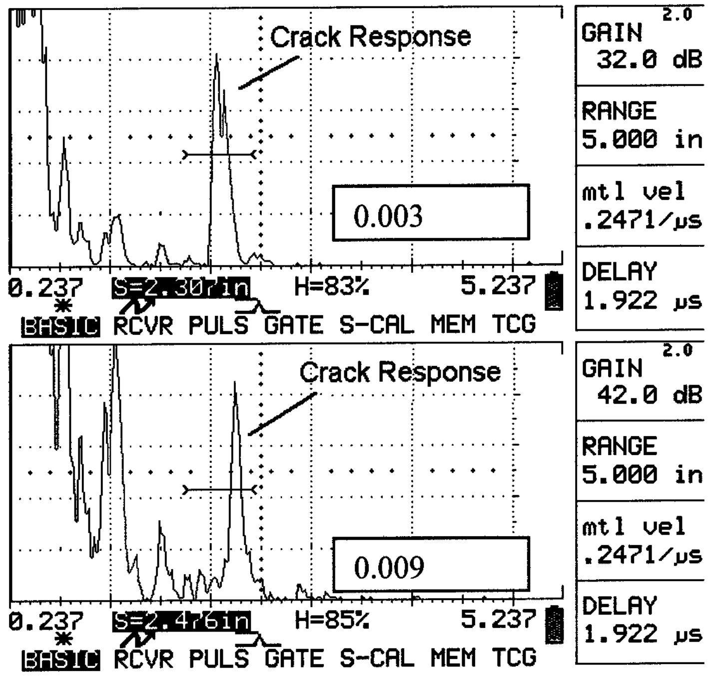
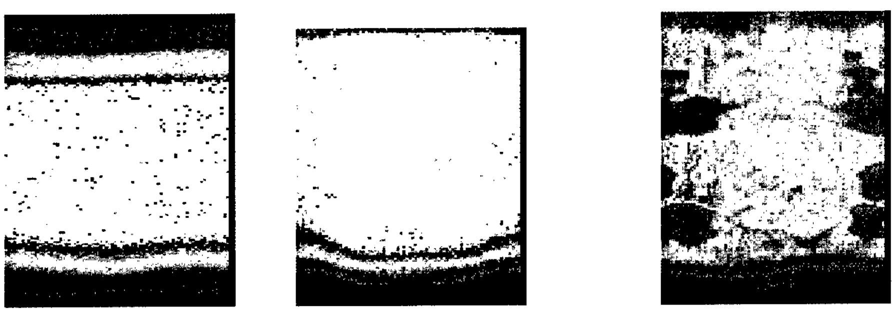
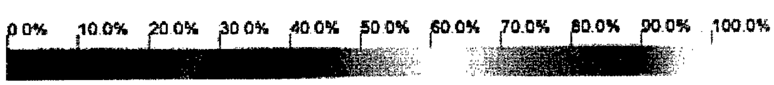


Figure 6-8. Ultrasonic Detection of Crack Beneath HVOF WC/CoCr Coatings (Boeing)

This method has not been used for depot evaluation as depots generally do not have test equipment of the required sophistication.



Standard **WC/Co 10,000 cycles @ 160 ksi; R = -1** **WC/CoCr 3,500 cycles @ 160 ksi; R = -1**



0% reflection (total delamination) "good" 100% reflection (no delamination)

Figure 6-9. Ultrasonic Measurement of Delamination of HVOF Coatings During Fatigue (R. Ware, AFRL)

6.4.4. Barkhausen Noise measurement of grind burns

Heroux Devtek has evaluated the Barkhausen Noise response for detection of grind burning and other damage beneath HVOF coatings [6.6].

Figure 6-10 shows that the Barkhausen signal drops off more slowly with HVOF than with EHC coatings, permitting somewhat greater sensitivity with HVOF coated components. Figure 6-11 shows that the Barkhausen method can readily detect shot peening and grind burns beneath an HVOF coating. It can therefore be used for grind burn detection of HVOF-coated components just as it is with EHC-coated ones.

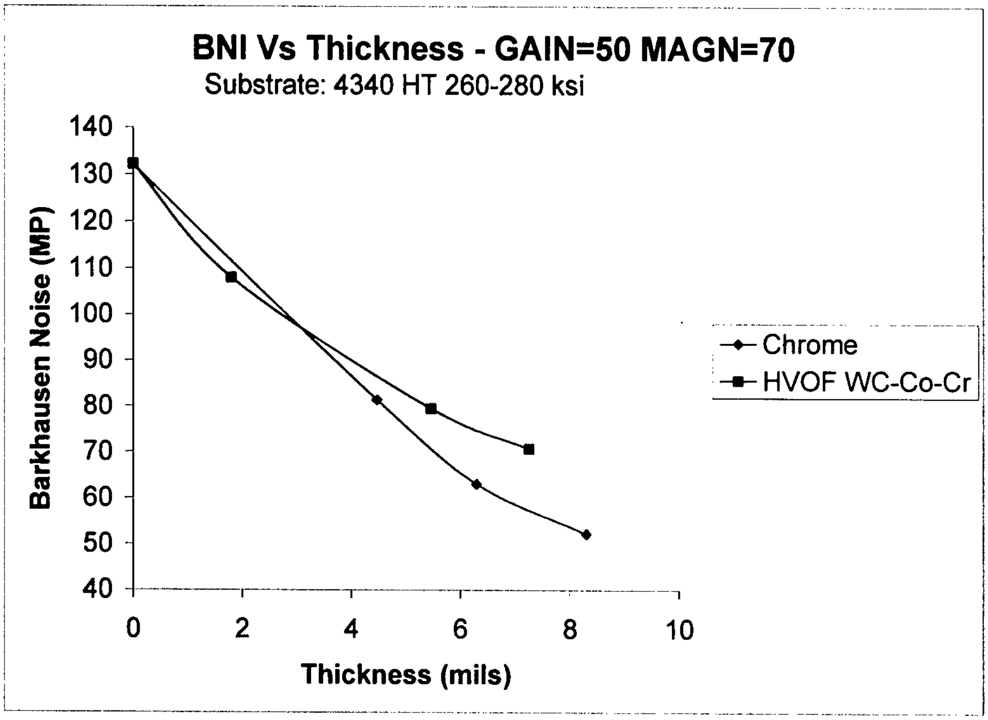


Figure 6-10. Barkhausen Noise Signal vs Coating Thickness (Heroux Devtek)

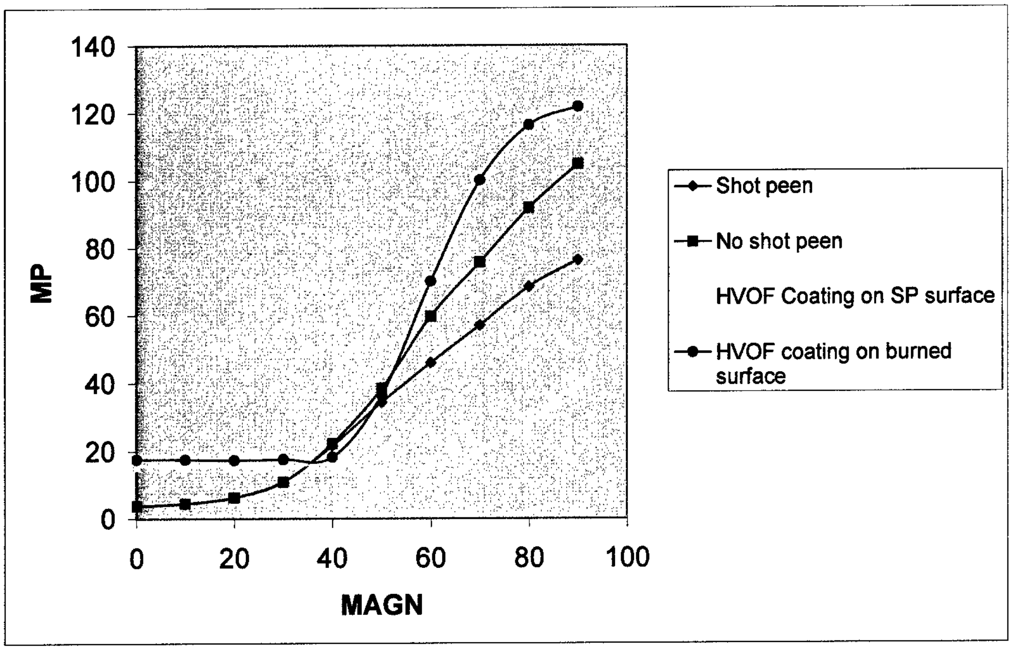


Figure 6-11. Effect of Shot Peening and Grind Burning on Barkhausen Noise of HVOF WC/CoCr (Heroux Devtek)

6.5. References

6.1 Nihad Ben Salah, Heroux Devtek, 21st HCAT Program Review, Toronto, Canada, September 2002 (available at www.hcat.org)

6.2 Nihad Ben Salah, Heroux Devtek, 22nd HCAT Program Review, San Diego, CA, April 2003 (available at www.hcat.org)

6.3 C. Edwards, Hill Air Force Base, at Meeting on Materials Substitution for Pollution Prevention in Advanced Aircraft – Technology Exchange, Baltimore, MD, September 2001 (available at www.hcat.org)

6.4 K. Rupel and L. Pfeiffer, Boeing St. Louis, 21st HCAT Program Review, Toronto, Canada, September 2002 (available at www.hcat.org)

6.5 R. Ware, Air Force Research Laboratory, 17th HCAT Program Review, Kennedy Space Center, December 2000 (available at www.hcat.org)

6.6 Nihad Ben Salah, Heroux Devtek, 21st HCAT Program Review, Toronto, Canada, September 2002 (available at www.hcat.org)

7. Cost Benefit Analysis

7.1. Introduction

To quantify the economic feasibility of implementing HVOF WC/Co and WC/CoCr, a CBA was performed focusing on a commercial landing gear overhaul facility that manufactures and maintains the majority of U.S. and Canadian C-130 landing gear. The company is considering implementation of HVOF equipment, and is a member of the Hard Chrome Alternatives Team (HCAT).

Information about current hard chrome electroplating operations at the facility was used to estimate the economic impact that may be expected if some hard chrome electroplating is replaced by HVOF thermal spraying. This CBA focuses on the impact on the C-130 Canadian and United States programs. The results of this CBA were intended to assist OEMs and DoD facilities in decisions related to replacing hard chrome electroplating.

7.2. Approach

Data collection and financial analyses of the data were performed using the JG-PP CBA Methodology. In accordance with this methodology, baseline process flow diagrams associated with current hard chrome electroplating processes were developed (refer to Figure 7-1). This generic flow diagram is based on information provided by the company. In general, each of the repaired and overhauled C-130 components addressed in this CBA requires two plating steps (shown as "Repeat as needed" in Figure 7-2). New production parts require one plating step. Rework steps are shown because some components may be improperly coated and require stripping and re-plating.

Data collection forms were developed to collect information on the baseline hard chrome electroplating operations. A site visit was performed collect the data, and information was collected in accordance with the JG-PP CBA Methodology. During the site visit, interviews were held with plating engineers, plating operators, plating supervisors, chemists, and other employees throughout the facility. The information gathered during the site visit was supplemented with correspondence after the visit. Where available, material usage rates and costs, labor hours, and waste treatment and disposal costs were identified. Where data were not available, values were assumed based on data from other facilities and using engineering judgement.

Environmental, safety, and occupational health (ESOH) activity costs were also obtained where available, or estimated. Some costs that may be associated with ESOH activities are listed below (refer to the data collection forms in the Cost Analysis Report Appendix for all ESOH activities considered):

- Lost productivity from worker exposure to the HazMats associated with hard chrome electroplating and from the use of personal protective equipment (PPE)
- Maintaining an accumulation point for waste
- Purchasing and maintaining PPE

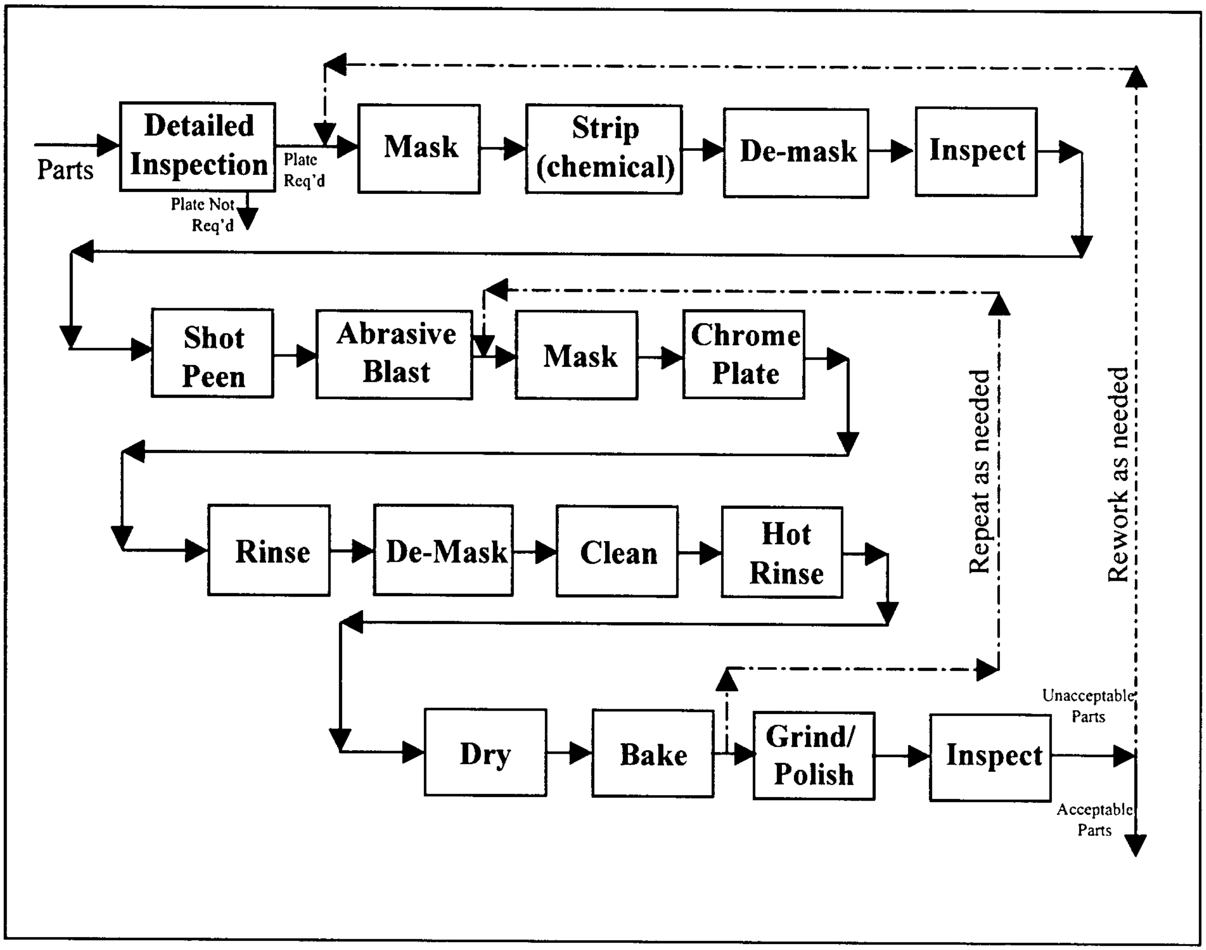


Figure 7-1. EHC Process Flow at Commercial MRO Shop

- Purchasing and storing drums, labels, and shipping materials associated with waste
- Heating and cooling air from losses due to hoods used for the chrome plating tanks.

The collected operating information was used to estimate the potential financial impact of the project, in accordance with the JG-PP CBA Methodology. A process flow diagram relating to the application of WC/Co or WC/CoCr by HVOF thermal spraying was also developed to aid in analysis of the data. A generic process flow diagram for HVOF WC/Co and WC/CoCr is shown in Figure 7-2. Note that five process steps (Rinse, Clean, Hot Rinse, Dry, and Bake) are expected to be eliminated when transitioning from hard chrome electroplating to HVOF thermal spraying.

The analysis does not include any effects on aircraft operating costs caused by the difference between the density of the HVOF coatings and the density of electroplated hard chrome. All dollar figures in this report are U.S. dollars.

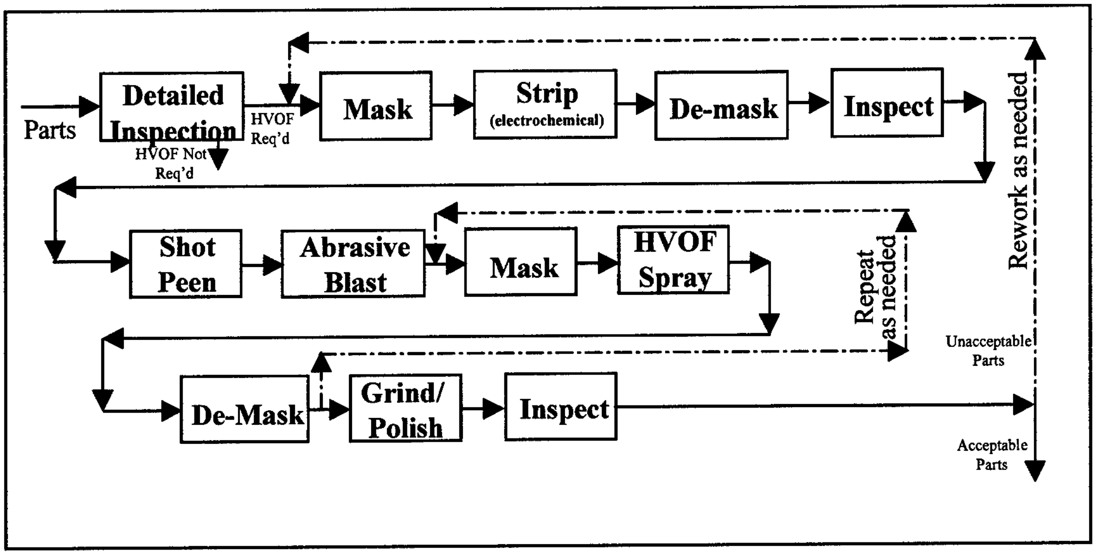


Figure 7-2. Projected Process Flow of HVOF for Applying WC/Co or WC/CoCr

7.3. Data and assumptions

The approximate number of U.S. and Canadian C-130 landing gear components that are hard chrome electroplated annually at the MRO facility is shown in Table 7-1. This number does not include rework of components; the actual number of components processed may be larger. Workloads can vary from year to year, but the values were considered to be representative of a standard annual workload.

Table 7-1. Annual Number of C-130 Landing Gear Components Chrome Electroplated at MRO Facility

Component	Fabrication (#/yr)	Repair/Overhaul (#/yr)
Main landing gear piston	200	500
Nose landing gear piston	30	250
Nose landing gear cylinder	20	250

Based on the annual chromic acid usage, it was estimated that the operation uses approximately 13,000 pounds (lb) of chromic acid each year for hard chrome electroplating the affected areas on the C-130 landing gear components. Affected areas of the components, which are areas forecasted for transitioning from hard chrome electroplating to HVOF thermal spraying for the purposes of this CBA, are shown in Figure 7-3. This figure identifies the components and areas to receive HVOF during fabrication and repair/overhaul. These parts were selected as likely components for transitioning because they have the largest external chrome plated surfaces, which would be suitable for transitioning to HVOF coatings. Additionally, these components frequently require stripping and replating during the overhaul process.

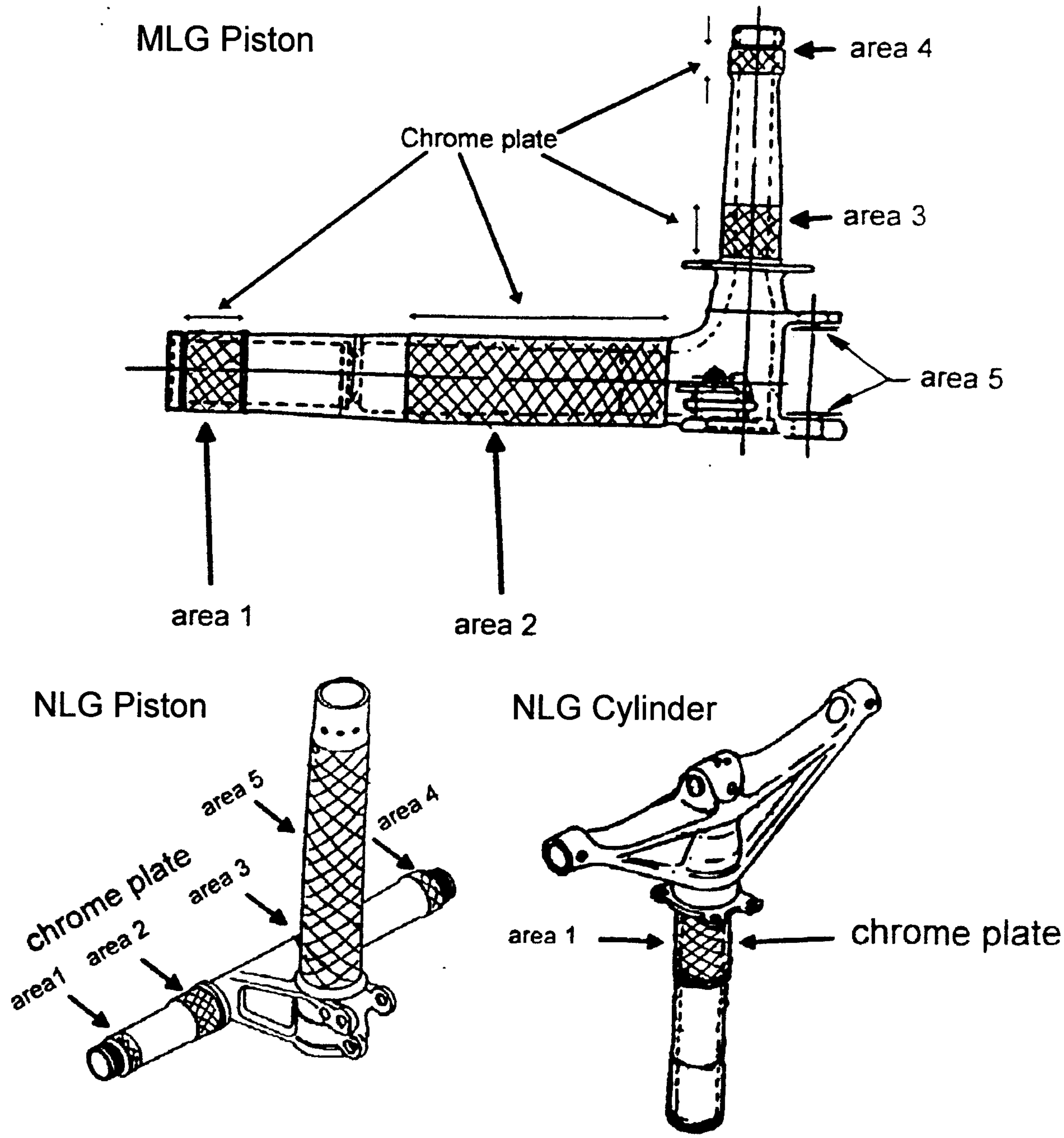


Figure 7-3. Areas Expected to be Transitioned from Hard Chrome Electroplating to HVOF Thermal Spraying

Due to sensitivity of operating data, remaining detailed data and calculations are not shown in this report. However, all data collected are on file. Types of data that were collected are listed in Section 7.3.1. HVOF materials and equipment considered in this CBA are described in Section 7.3.2. Assumptions made to complete the analysis are described in Section 7.3.3.

7.3.1. Data Provided by MRO facility

The information listed below was collected. Estimated cost impact on the C-130 was based on eliminating chrome plating from their MRO facilities. The quantities of materials used were based on data collected for the year 1999 and the forecast for the year 2000.

Current Hard Chrome Electroplating Operations:

A. The process steps focused on in this study include abrasive blast, mask, chrome plate, de-mask, and bake (refer to Figure 7-1).

B. Annual number of affected C-130 components that are fabricated or repaired and overhauled at the facility (refer to Table 7-1).

C. The frequency that the chrome plated areas on the C-130 landing gear that are processed for repair and overhaul require re-plating (after "Detailed Inspection" in Figure 7-1).

D. The average rework rate of C-130 landing gear components due to rejections after chrome plating was estimated to be 2%. The annual cost of reworking the components was estimated by the MRO facility.

E. Average size of a lot at the chrome plating operation.

F. Total number of electroplating personnel.

G. Labor requirements and turn around time (TAT) for each of the chromium electroplating process steps (refer to Figure 7-1).

H. Labor requirements for maintenance of the chrome plating baths, including cleaning, make-ups, and addition of chemicals to the tanks.

I. Types of inputs (i.e., materials, energy, and labor) and outputs (e.g., air emissions, wastewater, and hazardous waste) associated with the hard chrome electroplating process steps identified in Figure 7-1.

J. Chrome plating tank sizes and volume.

K. The temperature of the chrome plating tanks.

L. The average chrome plated coating thickness for fabricated components is 5 mils (prior to grinding). The average chrome plated coating thickness for repaired and overhauled components is 10 mils (prior to grinding).

M. Material usage and costs for chromic acid, sulfuric acid, lead anodes, sodium hydroxide, sodium carbonate, vinyl tape, lead tape, wax, and deionized water.

N. Energy usage related to baking the three affected components was provided. Bath heating costs were difficult to evaluate since they are hidden in a larger central heating system cost. However, since bath temperatures were 130-140°F, it was assumed that the energy consumption for heating the baths was considerably less than the energy costs for baking.

O. Annual energy usage for plating the affected components.

P. Chrome plated volume prior to grinding on each of the three affected components.

Q. Types and quantities of PPE used for electroplating activities and cost per PPE item.

R. Laboratory tests associated with process control for the chrome plating line, frequency of the tests, and labor required per test.
S. Labor requirements for metallurgical tests for the three affected components.
T. The cost of test panels for tests associated with the three affected components.
U. Heating and cooling costs from losses due to hoods for the chrome plating tanks was provided.
V. A description of the current wastewater treatment process was provided.
W. The annual costs associated with treatment of rinse water and wastewater from the scrubbers, and disposal of chromium solutions and solid waste from the scrubbers was provided.

Transitioning from Hard Chrome Electroplating to HVOF WC/Co and WC/CoCr:

The company provided information and assumptions related to implementing HVOF WC/Co or WC/CoCr to replace hard chrome electroplating on the affected C-130 landing gear components. These data and assumptions are described below.

A. SM5847 is being considered as the WC/CoCr material to be implemented.
B. Affected C-130 components and the areas on the components expected to transition from hard chrome electroplating to HVOF thermal spraying (refer to Figure 7-3). The parts were selected because they have large chrome plated surfaces, represent a large percentage of the total overhaul workload, and are suitable for transitioning to HVOF.
C. If HVOF is implemented, two chrome plating tanks and one chrome stripping tank could be shut down.
D. Upgrades of hard chrome electroplating equipment that could be avoided in the next 15 years if these tanks are shut down due to implementation of HVOF thermal spraying.
E. The surface areas of the affected C-130 component areas.
F. Transitioning to HVOF will not affect the current abrasive blasting process.
G. The HVOF coating will be applied to the same thickness as the current hard chrome electroplated coatings.
H. No labor or other cost changes are expected for:
   - Reporting associated with air emissions
   - Sampling and analysis of air emissions (no sampling is currently performed), wastewater effluents, and hazardous waste
   - Record keeping and reporting related to the use of HazMats
   - Other reporting, such as spill/emergency plans
   - Maintaining a hazardous waste accumulation point
   - Internal ESOH auditing and other auditing
   - Maintaining Material Safety Data Sheets (MSDSs)
   - Providing safety and other training for employees

- Providing medical exams (same requirements regardless of location at facility).

I. The company is currently in compliance with all associated regulatory permits, and expects to remain in compliance, so no savings from avoiding fines are expected by transitioning to HVOF.

J. Hard chrome electroplating processes are not expected to be moved to other locations because of compliance issues, so the project will not eliminate future relocation expenses.

7.3.2. HVOF Materials and Equipment Considered

In this analysis, three types of HVOF spray equipment were evaluated: Diamond Jet 2600, Diamond Jet 2700, and TAFA JP5000. For each type of equipment, estimates of effects on the C-130 fleet were made for WC/Co and WC/CoCr materials. The material- and equipment-specific information and assumptions are listed below.

<u>WC/Co powder</u>

A. WC/Co powder costs approximately $32/lb, based on a quote from a potential supplier of this material.

<u>WC/CoCr powder</u>

A. WC/CoCr powder costs approximately $32/lb, based on quote from a potential supplier of this material.

<u>Diamond Jet 2600 (Sulzer Metco)</u>

A. This type of equipment uses hydrogen as a fuel.
B. For Diamond Jet 2600 equipment, the average cost of fuels and related materials is approximately $33.33 per hour of WC/Co or WC/CoCr powder sprayed.

<u>Diamond Jet 2700 (Sulzer Metco)</u>

A. This type of equipment uses propylene as a fuel.
B. For Diamond Jet 2700 equipment, the average cost of fuels and related materials is approximately $33.33 per hour of WC/Co or WC/CoCr powder sprayed.

<u>TAFA JP5000 (TAFA)</u>

A. This type of equipment uses kerosene as a fuel.
B. For JP-5000 equipment, the average cost of electricity, gases, air, and water is approximately $1.20 per pound of WC/Co or WC/CoCr powder sprayed.

<u>General material and equipment information and assumptions</u>

A. The HVOF spraying rate used for applying HVOF coatings will be 10 lb/hr.
B. HVOF WC/Co deposit efficiency is approximately 50%.
C. An average HVOF gun barrel costs approximately $108, and must be replaced after 10 hours of spraying powder.

D. On average, one HVOF spray cell can process one landing gear component with HVOF in approximately 40 minutes. Actual spraying of WC/Co powder is assumed to be approximately 50% of this time, while the rest of the total processing time is assumed to be used for setting up the part and spray pattern.

7.3.3. Assumptions About Current and Future Operations

The other data collected and assumptions used to complete the economic analysis for this CBA are listed below.

A. The average number of U.S. and Canadian C-130 aircraft was provided by the U.S. Air Force and the Canadian Department of Defence.

B. On average, U.S. C-130 landing gear are overhauled approximately every eight years (provided by the U.S Air Force). It was assumed that the Canadian C-130 landing gear are on the same eight year overhaul cycle.

C. The number of landing gear components hard chrome electroplated annually will remain constant for the entire 15-year study period unless HVOF is implemented.

D. Current electroplating area labor rates are $65 per hour (fully loaded).

E. The labor rate for HVOF thermal spraying is the same as the labor rate for electroplating ($65/hr fully loaded).

F. The cost of rework for HVOF coating is the same as the cost of rework for electroplating.

G. The peening, grinding, and inspection steps will remain essentially unchanged when transitioning to HVOF coating. The company had also indicated that abrasive blasting would not be impacted. Note that application of WC/Co or WC/CoCr will lead to a requirement for diamond grinding wheels (the chrome plating process uses aluminum oxide wheels). The diamond grinding wheels are expected to last longer than conventional grinding wheels, even when grinding the HVOF coatings. The additional useful lifetime of the diamond grinding wheels is expected to offset the higher purchase cost of the diamond wheels.

H. It was assumed that the HVOF systems evaluated have a useful lifetime of at least 15 years.

I. Labor costs for masking and fixturing C-130 landing gear components for HVOF was assumed to be the same as for hard chrome electroplating.

J. Fixturing costs were estimated to cost $3,000 per landing gear part and would be replaced every 5 years.

K. The operation of the HVOF system to apply WC/Co or WC/CoCr to C-130 landing gear components will be optimized before full implementation to reach maximum efficiency.

L. The traditional technique of Fluid Penetrant Inspection is not expected to work on HVOF coatings. A new technique will be required, which may increase or decrease costs. For the purposes of this report, the cost was assumed to remain constant.

M. Stripping material costs were estimated for chrome plating and HVOF thermal spraying (based on published literature).

N. The net cost for disposing of waste WC/Co or WC/CoCr is zero, because the material can be sold to a third party for reprocessing, with the proceeds offsetting any internal handling costs.

O. Lifetime cartridge-type air filters will be used for filtering particulates from the HVOF WC/Co spray booth so material costs will not be affected by filters. This type of filter is currently used at other facilities, such as Naval Aviation Depot - Jacksonville, Florida.
P. The cost of installing electrolytic stripping tanks for removing HVOF coatings was not included in capital costs. The annual material and utility costs for stripping WC/Co or WC/CoCr were included in the analysis.
Q. The company will eliminate hard chrome electroplating of C-130 landing gear components on both fabrication and repair operations. As a result, removal of hard chrome electroplated coatings from C-130 landing gear components will eventually cease altogether.
R. The annual quantity of C-130 landing gear fabricated during the 15-year study period was assumed to remain constant.
S. The useful lifetime of a landing gear component coated with WC/Co by HVOF will be approximately 50% longer than the useful lifetime of hard chrome electroplated landing gear components. This increase in landing gear lifetime is based on results of current ESTCP testing, published literature, and engineering judgement; some recent testing has shown wear resistance between 2.5 and 4 times as great as that of electroplated chrome. However, the effects of increasing the useful lifetime of C-130 landing gear components was not considered in this analysis per the request of the MRO shop.
T. Reducing the number of C-130 landing gear components HVOF coated will proportionally reduce material, labor, waste disposal, and worker health and safety costs.
U. An estimate of approximately 1,200 landing gear components processed per year was used for this analysis; this number will remain the same after HVOF implementation. The coating thickness of electroplating and HVOF will also remain the same. However only 88% of the total component surface area will be transitioned to HVOF due to line of site issues, 12% of the total component surface area will continue to be electroplated after HVOF implementation.

Benefits from decreased turn-around time (TAT) of landing gear was also included in this CBA. Because the company has reported no difficulty in meeting required schedules for processing aircraft C-130 landing gear components, the cost avoidance associated with decreased TAT is not expected to accrue directly to the company after implementing HVOF. The assumptions relating to TAT are listed below.

A. The average TAT for C-130 landing gear components coated with WC/Co by HVOF will be approximately five days less than the average TAT for hard chrome electroplated C-130 landing gear components. This reduction includes process time, but not waiting/staging time.
B. The average value of a C-130 landing gear component is estimated at $60,000.
C. The annual interest rate used to calculate the "inventory cost" for landing gear is 3.2%; this is consistent with the 10-year real interest rate listed in Office of Management and Budget (OMB) Circular Number A-94 (January 2001 revision).

7.4. Annual operating cost avoidance

Data and assumptions described in Section 3 were used to calculate the current annual operating costs for coating C-130 landing gear components using the baseline hard chrome electroplating process. These data and assumptions were also used to estimate the annual operating costs for fabricating and overhauling C-130 landing gear components with HVOF. The annual operating cost avoidances reported in this section were derived from comparing the operating costs of the baseline hard chrome electroplating process to those calculated for the three types of HVOF equipment and two types of materials described in Section 7.3.2.

Table 7-2 shows the average annual operating cost avoidances that were estimated for implementing HVOF to replace hard chrome electroplating of C-130 landing gear components. It is expected that the average number of landing gear that need to be repaired and overhauled will decrease beginning in the eighth year after implementation, because of superior performance and durability of WC/Co coatings applied by HVOF. However, Heroux did not want to include these cost saving because they are not sure when the coating will be proven enough to decrease their refabrication schedule. Scenario 2 includes a benefit from reduced TAT, which is not expected to accrue directly to the MRO company.

Table 7-2. Estimated Annual Operating Cost Avoidance

Annual Operating Cost Avoidance[a]	
Labor	$113,540
Materials	$75,520
Utilities[b]	$11,390
Waste Disposal	$2,900
Additional Cost Avoidance due to Reduced TAT (Scenario 3)	$32,880
Total	$236,230

[a] Based on 1,250 per year total components processed and 1700 in^3 of the three components electroplated; after HVOF implementation assumes 1500 in^3 HVOF coated and 200 in^3 electroplated.

[b] Average of equipment and material types

7.5. Comparison of calculated results with vendor quotes

In addition to performing the calculations operating data to determine the cost avoidance that may result from transitioning from hard chrome electroplating to HVOF thermal

spraying, quotes from shops were obtained for chrome plating and HVOF spraying the three affected components. Quotes for hard chrome plating the components were obtained from Southwest Aeroservices in Tulsa, Oklahoma. Quotes for HVOF thermal spraying the components were obtained from Engelhard in East Windsor, Connecticut, Southwest Aeroservices in Tulsa, Oklahoma, and Hitempco in Old Bethpage, New York. For the quotes, the shops assumed that the parts were provided to them with the paint removed; one shop quoted for parts ready to coat (plating removed) the other two shops quoted for removing the chrome plating and re-applying either the chrome plating or applying HVOF thermal sprayed coating. A summary of their quotes and the cost difference are provided in Table 7-3.

Table 7-3. Summary of Vendor Quotes

Part	In-house Chromium plating (including stripping)	Out-source Chromium plating (including stripping)	In-house HVOF (including stripping)	Out-source HVOF (including stripping)	In-house HVOF (without stripping)	Out-source HVOF (without stripping)
Main Landing Gear Piston	$2,002	$3,400	$1,587	$3,700	$1,322	$934-$942
Nose Landing Gear Cylinder	$1,335	$1,600	$1,058	$1,250	$881	$166-$262
Nose Landing Gear Piston	$418	$3,000	$331	$3000	$276	$508-$1,012

7.6. Financial evaluation

To measure the financial viability of this project, three performance measures for investment opportunities were used: net present value (NPV), internal rate of return (IRR), and payback period. The NPV is the difference between capital investments and the present value of future annual cost benefits associated with the alternatives. The IRR is the discount rate at which NPV is equal to zero. NPV and IRR account for the time value of money, and discount the future capital investments or annual cost benefits to the current year. The payback period is the time period required to recover all of the capital investment with future cost avoidance. For NPV and IRR, a 3.2.0% discount rate was used for this financial evaluation, which is consistent with the OMB Circular Number A-94 and the ECAM. Guidelines for these performance measures are listed in Table 7-4.

Table 7-4. Summary of Investment Criteria

Criteria	Recommendations/Conclusions
NPV > 0	Investment return acceptable
NPV < 0	Investment return not acceptable
Highest NPV	Maximum value to the facility
IRR > discount rate	Project return acceptable
IRR < discount rate	Project return not acceptable
Shortest payback period	Fastest investment recovery and lowest risk

Adapted from *ECAM Handbook*.

A summary of the financial evaluation for implementing HVOF to replace hard chrome electroplating of C-130 landing gear components is shown in Table 7-5. This financial evaluation includes the range of annual operating cost benefits reported in Section 4 and the NPV based on a 15-year study period. The evaluation summarized in Table 7-5 does not include the costs of validation testing. The 15-year NPV for the surveyed facility ranges from a minimum of $1,799,700 to $1,977,500. The actual savings achieved at the facilities will vary depending on the number of actual applications converted, future workloads, and other factors specific to each facility.

Table 7-5. Results of Financial Evaluation for Direct Implementation

Category	Calculated Result
Annual Operating Cost Avoidance	$195,600 - $210,700
Initial Capital Investment	$700,450
Net Present Value [a]	$1,156,100 - $1,283,700
Internal Rate of Return [a]	30.5 – 32.8%
Discounted Payback [a]	3.29 – 3.53 years

[a] This value was calculated with Pollution Prevention Financial Analysis and Cost Evaluation System (P2/FINANCE) software program. This software program is proprietary and copyrighted by Tellus Institute of Boston, Massachusetts. A 15-year analysis and 3.2% discount rate were assumed.

NPVs for 5-year, 10-year, and 15-year study periods were calculated to facilitate comparing other financial analyses to this economic analysis of implementing HVOF. Table 7-6 shows the 5-year, 10-year, and 15-year NPVs calculated for the different scenarios.

Table 7-6. Net Present Value by Scenario

Scenario	5-year NPV	10-year NPV	15-year NPV
Tafa equipment/WCCo coating	$423,150	$1,283,700	$1,977,500
Tafa equipment/WCCoCr coating	$398,600	$1,238,200	$1,914,000
Sulzer-Metco equipment/ WCCo coating	$383,900	$1,211,000	$1,876,100
Sulzer-Metco equipment/ WCCoCr coating	$354,300	$1,156,100	$1,799,700

[a] The numbers were rounded to the hundreds place.

7.7. Summary and recommendations

HVOF application of WC/Co and WC/CoCr is being investigated as an alternative to hard chrome electroplating for fabricating and repairing/overhauling aircraft landing gear. A CBA was performed to identify the potential financial impact of implementing these HVOF coatings for application to C-130 aircraft landing gear components. Data were collected at this facility and the potential economic effects were calculated in accordance with the JG-PP CBA Methodology.

It was estimated that the use of HVOF for C-130 landing gear components will result in a net decrease in annual operating costs at Heroux. The annual operating costs savings range from $195,600 to $210,700 based on a number of differing assumptions described in this CBA. This analysis assumes that HVOF WC/Co or WC/CoCr will be implemented only for use on the affected C-130 landing gear components. Although the material costs for the HVOF WC/Co or WC/CoCr powders are the same, their densities and deposit efficiencies vary. This is the cause of higher operating costs for the WC/CoCr material as shown in Table 7-6. The primary difference between the equipment types is the fuel type used. The Diamond Jet 2600 uses hydrogen as a fuel, the Diamond Jet 2700 uses propylene, and TAFA JP5000 uses kerosene. The difference in fuel costs is the reason that the Tafa equipment shows a more positive NPV. A reduced labor requirement with HVOF implementation was the primary cost driver in this analysis.

Additional cost savings that would be realized is the estimated 50% extension of service life over the service life of electroplated chrome that is expected to be realized with HVOF WC/Co or WC/CoCr implementation. This was not done at the request of Heroux. Since a WC/Co and WC/CoCr applied by HVOF has reportedly shown wear resistance up to four times as great as that of electroplated chrome in some recent laboratory investigations. Therefore, greater benefits to the C-130 program may be

realized through implementation of the HVOF coatings due to increased service life of landing gear components. This scenario would further reduce labor requirements and have a corresponding reduction in labor and material costs.

Outsourcing landing gear coating was analyzed and this analysis indicates that it is more cost effective to conduct chromium plating and HVOF in house. One vendor quote indicated that outsourcing HVOF after stripping in-house would be a cost effective decision. However it should be noted that labor costs for stripping were based on estimates and further evaluation of this scenario should be conducted to validate these results.

The MRO facility is considering implementing, independent of the results of this CBA, because they believe that the environmental issues associated with hexavalent chromium will eventually lead to further regulation of the material and of hard chrome electroplating. If this is the case, operating costs for chromium plating would increase above that shown in this report, making HVOF implementation even more financially beneficial.

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8. Specifications and Standards

In order to use the HVOF process in manufacturing or repair it is essential for engineers to be able to refer to specifications for HVOF deposition and processing. To facilitate this HCAT has developed specifications for both HVOF materials and deposition on high strength steel and for grinding.

Prior to the HCAT program only the Boeing specifications were widely used:

- BAC 5851 for thermal spray deposition, supported by Boeing Materials Spec BMS 10-67, defining thermal spray powders, and
- BAC 5855, which specifies grinding methods for thermal spray coatings.

The primary standards and specification body for aerospace specifications is the Society of Automotive Engineers (SAE), who issue Aerospace Materials Specifications (AMS specs). Obtaining AMS specifications involves drafting the specifications and working closely with the SAE AMEC committees over a period of one to three years to create a document that is satisfactory for all committee members. A general HVOF specification, AMS 2447, was developed by Bruce Bodger of Hitemco, a member of the HCAT team. During this program specifications for HVOF powders and deposition methods were developed by Donald Parker (NASA KSC), and specifications for grinding of HVOF coatings were developed by Jon Deveraux (NADEP Jacksonville), both members of the HCAT team. These specifications and their status are shown in Table 8-1. The specifications developed in this program are reproduced below.

Table 8-1. SAE Aerospace Material Specifications for HVOF

Specification	Title	Notes
AMS 2447B (1998)	Coating, Thermal Spray High Velocity Oxygen/Fuel Process	Original general HVOF spray specification developed by Bruce Bodger
AMS 2448 (2003)	Application Of Tungsten Carbide Coatings On Ultra High Strength Steels High Velocity Oxygen / Fuel Process	Developed for use on landing gear and other high strength steel by Don Parker
AMS 7881 (2003)	Tungsten Carbide-Cobalt Powder	Powder specification for HVOF WC/Co coatings, developed by Don Parker
AMS 7882 (2003)	Tungsten Carbide-Cobalt Chrome Powder	Powder specification for HVOF WC/CoCr coatings, developed by Don Parker
Not yet issued	Grinding Of HVOF Sprayed Tungsten Carbide Coatings Applied To High Strength Steels	HVOF grinding specification developed by Jon Deveraux

8.1. Proposed AMS 2448

APPLICATION OF TUNGSTEN CARBIDE COATINGS ON ULTRA HIGH STRENGTH STEELS

High Velocity Oxygen / Fuel Process

AMEC00AB DRAFT

Donald S. Parker, Sponsor

1.0 SCOPE

1.1 Purpose

This specification covers engineering requirements for applying tungsten carbide thermal spray coatings to ultra high strength steels (220 ksi and above) utilizing high velocity oxygen fuel (HVOF) combustion driven processes and the properties for such coatings. The processes and procedures herein apply only to the properties of the as-deposited coating.

1.2 Application

This process has been used typically to provide coatings of lower porosity and higher adhesive, and/or cohesive, strength than generally attainable with plasma spray; and for applications requiring wear, heat, and corrosion resistance or dimensional restoration that were traditionally chrome plated. However, usage is not limited to such applications.

1.3 Safety - Hazardous Materials

While the materials, methods, applications, and processes described or referenced in this specification may involve the use of hazardous materials, this specification does not address the hazards which may be involved in such use. It is the sole responsibility of the user to ensure familiarity with the safe and proper use of any hazardous materials and to take necessary precautionary measures to ensure the health and safety of all personnel involved.

2.0 APPLICABLE DOCUMENTS

2.1 The following publications form a part of this specification to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other ublications shall be the issue in effect on the date of the purchase order.

2.2 S.A.E. Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AMS 2447 Coating, Thermal Spray High Velocity Oxygen/Fuel Process

AMS S13165, Shot Peening of Aircraft Components

SAE J442 Test Strip, Holder, and Gage for Shot Peening

AMS 6484 Steel, Bars, Forging, and Tubing

AMS 6454 Sheet Steel, Strip, and Plate

AMS 7881 (AMEC 99B) Tungsten Carbide-Cobalt Powder

AMS 7882 (AMEC 99C) Tungsten Carbide-Cobalt Chrome Powder

2.3 ASTM Publications: Available from ASTM, 100 Barr Harbor Drive, West Conshocken, PA 19428-2959

ASTM C 633 Adhesion or Cohesive Strength of Flame-Sprayed Coatings

ASTM E 384 Microhardness of Materials

ASTM E 18 Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials

ASTM E3 Standard Practices for Preparation of Metallographic Specimens

3.0 TECHNICAL REQUIREMENTS

3.1 Equipment

3.1.1 Torch: A specially constructed gun that utilizes combustion products to generate a high velocity gas stream for heating of the coating material to a molten or plasticized state, and transfer of the coating material to the work piece.

3.1.2 System: The system shall be microprocessor controlled and fitted with an automated device for regulating the gas(es) and fuel(s) used to operate the torch. The torch shall be mounted on an automated manipulating device during the deposition process to maintain a constant working distance and traverse rate, or maintained in a fixed position with the component mounted on a manipulating device that will maintain a constant working distance.

3.1.3 Gauges:

3.1.3.1 Pressure gauges shall have minumum accuracy of ± 1.5% of full scale

3.1.3.2 Flow meters shall have a minimum accuracy of ± 2% of full scale

3.1.4 Powder Feeder: The powder feed system shall supply a metered flow of material.

3.2 Materials

3.2.1 Gases and Fuels: Specifications utilized by the processor for procurement of these materials shall be acceptable to the purchaser.

3.2.2 Coating Material: Shall conform to AMS xxxx (AMEC 99B) or AMS xxxx (AMEC 99C) as required by the drawing or otherwise specified by purchaser. All powders shall be dry, free flowing and uniformly blended.

3.3 Preparation

3.3.1 Metallurgical Treatments: All metallurgical processes such as heat treating, shot peening, or similar should be completed prior to surface conditioning for spraying

3.3.2 Cleaning: Surfaces to be coated shall be thoroughly cleaned to remove moisture, oil, grease, dirt, scale, paint and foreign material. Final cleaning shall take place no more than four hours prior to coating. Cleaning procedures shall not cause hydrogen embrittlement or other detrimental surface contamination on surfaces that are to be coated.

3.3.3 Masking: Parts shall be masked by an appropriate means to protect all surfaces that are

not being coated.

3.3.4 Surface Conditioning: After cleaning, surface to be coated shall be grit blasted with aluminum oxide blast media at 60 – 80 psi and 6-8 inch standoff distance to clean and prepare the surface for HVOF deposition. Grit shall be free from moisture, oil, dirt and other contaminants. Grit size shall be of the finest possible size necessary to achieve a 120 – 150 Ra surface roughness, but shall never be coarser than 54 grit. A surface profilometer shall be used to verify the proper surface conditioning for each procedure used.

3.4 Application

3.4.1 Process: The parameters for gas flows and pressures, powder feed rates, and spray distance, as well as deposition rates and traverse speeds shall be determined by a statistical method designed to achieve the desired coating properties specified by this document and / or the purchaser.

3.4.2 Preheating: Surfaces to be coated shall be preheated to a sufficient temperature to remove moisture; however the maximum temperature during preheating shall not exceed 350 degrees F. Preheating may be accomplished by use of the torch or by other suitable means and shall be monitored as specified in 3.4.4.

3.4.3 Coating: The coating material shall be deposited on the designated surface in sufficient thickness to permit finishing to specified dimensions. The minimum finished coating thickness shall be greater than or equal to 0.003 inch.

3.4.3.1 Areas on which coating is optional, shall be exempt from minimum thickness limitation; however, if coated, the areas must be prepared and handled in the same manner as the area on which coating is required and adhesion requirements still apply.

3.4.3.2 A spray angle of 90 ± 5 degrees should be maintained. For cylindrical components, angle is measured relative to the centerline axis of the cylinder. For any application that requires spraying at less than 85 degrees, all test specimens shall be sprayed at the same angle as the component and all minimum mechanical property requirements will apply.

3.4.3.3 Spray deposition shall be continuous, except for interruptions to measure coating thickness and/or for cooling cycles to maintain part below maximum allowable temperature.

3.4.4 Substrate Temperature: Unless otherwise specified, maximum temperature of the substrate during preheating and coating application shall be controlled to not exceed 350 degrees F. Temperature measurements shall be made utilizing a laser sighted infrared thermometer with adjustable emissivity (0.1 to 0.99) and response time of less than 1 second. Measurement location shall be taken on the parent metal adjacent to the to the edge of the coating as it traverses the area to be coated. If geometric, or part size constraints do not allow this procedure to be followed, then the temperature shall be measured immediately adjacent to the coated area along the same path of travel as the gun plume. Emissivity shall be set to a standard value for high strength steel. Resolution of the IR thermometer shall be 1C or 1 F, depending on the scale used and spot diameter should be less than 2.5 inch or equivalent to the actual size of the IR beam.

3.4.5 Test Specimens: Specimens required under 3.7 shall be coated, as far as practicable, using the process procedures identified on the Coating Process Control Sheet for the parts that they represent. Coupons representing rotating components shall be sprayed at the same rotational speed and incremental step rate as the component. If there are multiple application angles on the same component, each of the deposition angles shall be

evaluated with coupons for compliance with minimum mechanical property limits. Coupons shall be evaluated prior to coating application on production components.

3.4.6 Specimen Material: Bond strength specimens shall be manufactured from AMS 6484, heat-treated to produce a hardness Rockwell C 40 minimum and no higher than the hardness of the component substrate. Metallographic and Bend test specimens shall be manufactured from AMS 6454 and heat-treated to produce a Rockwell C hardness greater than 40. Alternatively, test specimens can be made from the same material, in the same condition as the component.

3.5 Surface Finishing: Procedures for finishing shall be in accordance with purchaser's specifications.

3.6 Properties

3.6.1 Adhesion

3.6.1.1 Bend Test: Specimens prepared and tested in accordance with 3.7.1 shall not show separation of the coating from the substrate, when examined visually without magnification. Cracking of the coating and minimal separation at the specimen edges shall be considered acceptable.

3.6.1.2 Bond Strength: Specimens, prepared and tested in accordance with 3.7.2, shall be 10 ksi minimum.

3.6.2 Coating Hardness: The coating hardness, tested in accordance with 3.7.3 shall be HV_{300g} 950 minimum.

3.6.3 Microstructure: A detailed standard procedure for metallographic specimen preparation and examination shall be used to ensure consistent results as in 4.4.1. Examination of a suitably prepared cross-sectioned specimen shall show the coatings to be free from cracks and delaminations. Repolishing can only be performed on specimens that show flaws induced by the polishing method. Oxide content cannot be induced and is not grounds for re-polishing. Microstructural properties shall be evaluated in accordance with the following:

3.6.3.1 Voids / Oxides: Shall be uniformly distributed and not greater than 1% in any field of view (approximately 0.02 inch (0.51mm) length) when examined at 400x magnification on the cross sectioned specimen. Any single void greater than 0.002 inch (0.2mm) shall be cause for rejection.

3.6.3.2 Unmelted Particles: None in any field of view (approximately 0.04 inch (1.0mm) length) when viewed at 200x magnification on the cross sectioned specimen.

3.6.3.3 Interface: Contamination of the coating / substrate interface with surface preparation media shall not exceed 10% in any field of view (approximately 0.04 inch (1.0mm) length) when viewed at 200x magnification on the cross sectioned specimen. Any coating separation at the interface will not be acceptable. Separation is defined as gap between the coating and substrate greater than 0.002 inch in length following directly along the bond line. Any length less than this will be considered acceptable voids or porosity.

3.6.3.4 Carbide Distribution: In any 400x field of view, all carbides shall be uniformly distributed with no banding or clustering.

3.6.4 Residual Stress

3.6.4.1 Almen Strip: Coatings shall be evaluated for residual stress by preparing, and spraying a standard Almen Type "N" strip in identical fashion as the component being coated. Both the surface to be coated and uncoated surfaces of the Almen strip shall be grit blasted to minimize curvature of the Almen strip to less than 0.002 inches arc height. The arc height of the Almen strip surface to be coated shall be measured after grit blast surface preparation (first reading) and again after coating application (second reading). The first reading and subsequent coating application shall be with the convex surface of the Almen strip in the up position if the strip is not flat after grit blast and the second reading with the same surface, now coated, in the up position. The Almen strip shall be restrained flat, in the transverse direction by four screws located as indicated in AMS S13165C (Note: also covered in SAE J442) during coating deposition. The measured change in deflection of the Almen strip resulting from the application of the coating shall be reported as the difference of the two readings, second reading minus first reading, and is indicative of the desired compressive coating stresses if the sign of the difference is positive. Acceptable values for Almen type "N" strip arc heights are positive 0.003-0.012 inches for a 0.005-inch thick coating.

3.7 Test Methods

3.7.1 Bend Test: Test panels, 0.05 x 1x 3 inches +/- 0.05 inch (1.3 x 25 x 76mm) shall be coated on one side to a thickness of 0.001 to .003 inch (0.025 to 0.076 mm). Panels shall be tested by being bent around a 0.5 inch (13 mm) diameter bar, with the coated surface on the outside of the bend, at a rate of approximately ten degrees per second. Panels shall be bent to obtain a 90-degree permanent set.

3.7.2 Bond Strength: Test specimens, approximately 1 inch (25 mm) in diameter by 2 inches (51 mm) long, +/- 0.05 inch (0.5 mm) shall be coated to a thickness of 0.009 to 0.012 inch (0.2 to 0.3mm). Specimens shall be prepared and tested in accordance with ASTM C633. Adhesive only qualification tests shall be run under the same test conditions to verify integrity of the adhesive.

3.7.3 Microhardness: Test specimens, 0.05 x 1 x 3 inches, +/- 0.05 inch (1.3 x 25 x 76mm +/- 0.5 mm) shall be coated on one side to a minimum thickness of 0.009 inch (0.20 mm). The hardness shall be the average of a minimum of ten evenly spaced indentations in accordance with ASTM E 384.

3.8 Quality: The coating, as received by purchaser, shall be adherent to the basis material and shall have a uniform, continuous surface free from spalling, chipping, flaking, and other imperfections detrimental to usage of the coating.

3.9 Tolerances: Unless otherwise specified by the purchaser, a tolerance of -0 to +0.125 inch (3.2 mm) is allowed on the boundaries of the coated area.

3.10 Definition

3.10.1 Lot: A lot shall be all parts of a similar configuration, coated sequentially on the same machine setup using the same batch of coating material and process parameters, within a shift or eight hours of torch time, and presented for processor's inspection at one time.

3.11 Mechanical Coating Removal

3.11.1 Coatings may be removed by mechanical methods of grinding, or any method approved by purchaser as long as all original substrate conditions are duplicated.

3.12 Chemical Coating Removal

3.12.1 Equipment

3.12.1.1 Tank: A container of adequate volume for the stripping solution and the parts being stripped. The tank must be manufactured from materials such that the structure will not be degraded by the stripping solution.

3.12.1.2 Heaters: Heating devices approved for use with the required solution(s) and capable of reliably maintaining the specified solution temperature.

3.12.1.3 Rectifier: Approved electrical device for delivery of controlled DC current to the electrolytic stripping solution.

3.12.1.4 Controls: Indicating devices used to determine and maintain process temperature and current flow shall have minimum accuracy as follows:

Temperature Gages: +/- 2% of full scale

Current and Voltage Gages: +/- 5% of full scale

3.12.1.5 Agitation: Agitation or circulation of the solution shall be accomplished by either pumping low pressure, clean, dry air through the solution, or by mechanical agitation using impeller or propeller driven flow.

3.13 Materials

3.13.1 Approved stripping solutions and their methods of use are listed in Table 1

TABLE 1 – Stripping Solutions

Solution #	**Solution Name**	**Immersion Use**	**Electrolytic Use**
1	Rochelle Salt		X
2	Metal-X B929 Nickel Plating Strip	X	

3.14 Preparation

3.14.1 Composition and Control of Solutions:

Solution 1 – Rochelle Salt

Variable	**Control Limits**
Anhydrous Sodium Carbonate	20-30 oz./gal. Water (de-ionized optimum)
Sodium Tartarate (Rochelle Salt)	8-12 oz./gal. Water (de-ionized optimum)
pH	11.0 - 12.0
Temperature	104° – 150° F (140° – 150° Optimum) (40° – 65° C)
Voltage	4-6 volts DC
Current Density	4-8 amps / square inch
Solution Agitation	Dry, Oil Free Compressed Air

Solution 2 – Nickel Plate Strip Solution

Variable	Control Limits
METAL-X B929 Nickel Strip Solution (or equivalent)	2.5 lb./ gal. Water (de-Ionized optimum)
pH	9.2 – 9.8
Temperature	120° – 150° F (50° – 65° C)
Solution Agitation	Dry, Oil-Free Compressed Air

3.14.2 Solution Processing Requirements:

The processing solutions and equipment shall be kept clean at all times.

Operations shall be suspended and corrected when the following has occurred:

a) A non-removable smut is formed or foreign material is deposited on the component surface.

b) The solution temperature or composition is outside the control limits.

c) The solution surface has developed a surface film.

d) The parts have been etched.

e)The coating removal rate has diminished to less than 1 mil per hour.

3.14.3 Masking: The specified solutions may have an affect on other plated, painted or surface treated areas. Masking of those areas by impermeable means is required.

3.15 Stripping Procedures

3.15.1 Electrolytic Method:

Step 1 - A stainless steel cathode is required for this method. The coated part to be stripped is connected to the positive terminal conductor to act as the anode. Connection shall be made such that arcing is prevented.

Step 2 – Immerse the part into the bath and apply 4-6 volts DC at a current density of 4-8 amps per square inch of coated area to be stripped.

Step 3 – Check progress at least every 45 minutes to remove an accumulated smut. Use Scotch Brite ™ or equivalent to remove smut. Removal rate should be approximately 2-6 mils of coating per hour.

Step 4 – When coating is adequately stripped, remove the part from the tank and rinse thoroughly with water at room temperature. All remaining coating can be removed by grit blasting prior to re-application.

Step 5 – Dry part with compressed, dry, oil free air and apply any necessary in process corrosion preventative compound to prevent corrosion damage while part is in transit.

3.15.2 Immersion Method

Step 1 – Immerse part into prepared solution.

Step 2 – Check progress every 45 minutes and remove any accumulated surface smut. Use Scotch Brite ™ or equivalent to remove smut. Removal rate should be

approximately 1 mil of coating per hour.

Step 3 – When coating is adequately stripped, remove component from the tank and rinse thoroughly with water at room temperature.

Step 4 – Dry part with compressed air and apply any necessary in process corrosion preventative compound to prevent corrosion damage while part is in transit.

3.16 Post Strip Processing

3.16.1 The processes outlined above DO NOT involve evolution of atomic hydrogen at the coating surface, or base metal interface. Therefore, there is no susceptibility to hydrogen embrittlement of the component and post processing bake is not required.

4.0 QUALITY ASSURANCE

4.1 Responsibility for Inspection: Processor shall supply all test specimens for processor's tests and shall be responsible for performance of all required tests. When parts are to be tested, the purchaser shall supply such parts. Purchaser reserves the right to sample and to perform any conformity testing deemed necessary to ensure that the coating conforms to the requirements of this specification.

4.2 Classification of Tests

4.2.1 Acceptance Tests: Bend Test (3.6.1.1), Hardness (3.6.2), Microstructure (3.6.3), Thickness (3.4.3), and Tolerances (3.9) are acceptance tests, and shall be performed on each lot. For fatigue sensitive applications, Residual Stress (3.4.6) should be evaluated periodically as deemed appropriate by the processor and/or anytime process variables are changed.

4.2.2 Periodic Tests: The Coating Material Composition Verification (3.2.2) and Bond Strength (3.6.1.2) are periodic tests and shall be performed at a frequency selected by the processor unless otherwise specified by the purchaser.

4.2.3 Pre-production Tests: All technical requirements of this specification are pre-production tests and shall be performed prior to, or on the initial shipment of coated parts to a purchaser. In addition, these tests shall be performed when a significant change in material, and/or processing requires approval as in 4.4.3, and when purchaser deems conformity testing to be required.

4.3 Sampling and Testing

4.3.1 For Acceptance Tests: One or more sets of test specimens to represent each lot of parts.

4.3.2 For Periodic and Pre-production Tests: Sample quantity shall be selected at the discretion of the processor unless otherwise specified by the purchaser.

4.4 Approval

4.4.1 The processor shall establish a written process description of preparation, application, and inspection for each part number. The description shall include control factors and parameters that provide coated parts meeting specified requirements. Control factors considered proprietary by the processor shall be assigned codes within the process description. The processor shall maintain a complete record of proprietary factors and codes. These factors shall include sufficient information to reproduce the process. An example is shown in Figure 1.

4.4.2 The process description and control factors, and first article, whichever is specified, shall

be approved by the cognizant engineering organization before production coated parts are supplied.

4.4.3 The processor of coated parts shall make no significant change to the process description, or to the materials, processes, or controls referenced in the process description (see Figure 1) unless the change is approved by the cognizant engineering organization. A significant change is one, which could affect the properties or performance of the coating or substrate.

4.5 Reports: Processor shall furnish with each lot a report stating that the parts have been processed and tested in accordance with specified requirements and that they conform to the acceptance test requirements. The report shall include the purchase order number, lot number, AMS-xxxx, part number, quantity and numerical test results.

4.6 Re-sampling and Re-testing: If any acceptance test fails to meet specified requirements, disposition of parts may be based upon the results of tests on three additional specimens for each nonconforming specimen if coated within the same lot. Except as specified in 4.6.1, 4.6.2 and 4.6.3, failure of any retest to meet specified requirements shall be cause for rejection of parts represented. Results of all tests shall be recorded.

4.6.1 If any lot acceptance test fails to meet specified requirements, or the original sampling as in 4.3 and upon re-sampling as in 4.6, the parts in that lot may be stripped by the method specified in this document, or an alternate method acceptable to the purchaser. The parts may then be re-coated and re-tested. Whichever method is selected, the process shall not roughen, pit, or embrittle the basis material. Alternatively, all parts in that lot may be inspected for the nonconformance and nonconforming parts stripped and reprocessed.

4.6.2 If the results of any periodic test fail to meet the specified requirements, the process is nonconforming. No additional parts shall be processed until the process is corrected and new specimens are coated and tested. Results of all tests shall be recorded and when requested, reported. Purchaser shall be notified of all parts coated since the last successful test.

4.6.3 If a bond strength specimen fails at the adhesive bond joint, at a value less than the adhesion control specimen, or at a value less than the required minimum, the test result may be declared invalid and the test repeated. Such retest shall not be considered as one of the re-tests specified in 4.6.

5.0 PREPARATION FOR DELIVERY

5.1 Coated parts shall be handled and packaged to ensure that the required physical characteristics and properties of the coating are preserved.

5.2 Packages of parts shall be prepared for shipment in accordance with commercial practice and in compliance with applicable rules and regulations pertaining to the handling, packaging, and transportation of the parts to ensure carrier acceptance and safe delivery.

6.0 ACKNOWLEDGMENT

6.1 Processor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders.

7.0 REJECTIONS

7.1 Parts, which have non-compliant coating that does not conform to this specification, or to modifications authorized by purchaser, will be subject to rejection.

8.0 NOTES

8.1 Dimensions and properties in inch/pound units and the Fahrenheit temperatures are primary; dimensions in SI units and Celsius temperatures are shown as the approximate equivalent of the primary units and are presented only for information.

8.2 Procurement documents should specify not less than the following:

Type of coating desired and AMS designation

Coating thickness required

Coating acceptance criteria if not specified herein

Quantity of parts to be coated

8.3 Coatings meeting the requirements of this specification have been classified under Federal Standardization Area Symbol "MFFP."

8.4 Key Words: HVOF, Wear Resistant, Corrosion Resistance, and Dimensional Restoration

Figure 1

Coating Process Control Sheet

PROCESSOR:______________________________ COATING SPECIFICATION:___________

PURCHASER:____

APPLICATION:

PART NAME:____
PART NUMBER: ____________________________ BASIS MATERIAL:_______________

PREPARATION:

PRE-BLAST CLEANING:____

BLASTING GRIT TYPE:____________GRIT SIZE:__________PRESSURE:______________

BLASTING TIME, INTENSITY, and COVERAGE: _________________________________

SPRAY EQUIPMENT & ACCESSORY EQUIPMENT:

MANUFACTURER: _________________________________ TORCH: _________________

POWDER PORT: ______________ HEAD: _______________ NOZZLE: _________________

INJECTOR: OXYGEN: ___________ FUEL: _______________ POWDER: _________________

ADAPTORS:____

CONSOLE PARAMETERS:

OXYGEN: SUPPLY PRESSURE: __________________

TORCH PRESSURE: __________________FLOW RATE: ____________________

FUEL: TYPE: ______________________________ SUPPLY PRESSURE: _______________
TORCH PRESSURE: ___________________________ FLOW RATE: ____________________

POWDER FEEDER:

FEEDER TYPE: ____
CARRIER GAS: ___________________________SUPPLY PRESSURE:___________________

FEEDER PRESSURE:______________FLOW RATE: ______________DIAL: _______________

VIBRATOR USED: [ ]YES [ ]NO AMPLITUDE: ______________________________

FEEDER HOSE: DIAMETER:________________LENGTH:_____________________________

COATING PROCESS DATA:

PREHEAT TEMPERATURE: ______________ MAXIMUM PART TEMPERATURE: __________

COOLING, METHOD: ___________________ POSITION: ___________________________

COOLING, CYCLE TIME: ________________ SPRAY, CYCLE TIME:___________________

SPRAY, NO. OF CYCLES:________________ SPRAY, COATING THICKNESS:____________

WORK HANDLING:

PART MOTION: _________________________________ SPEED: ____________________

GUN MOTION: __________________________________SPEED: ____________________

GUN-TO-WORK: DISTANCE: _______________________ ANGLE: ____________________

SPRAY MASKING/FIXTURES: ____

METALLOGRAPHY:

MICROSTRUCTURE: _____________________________ HARDNESS: __________________

BOND STRENGTH: ______________________________ BEND TEST: ____________________

COATING MATERIAL: ___________________________ LOT/BATCH NO:_______________

OPERATOR: __________________________________ CERTIFICATION NO: ____________

APPROVAL: ____ DATE: ____________

PREPARED UNDER THE JURISDICTION OF AMS COMMITTEE "B"

8.2. Proposed AMS 7881

AMEC 99B DRAFT

SPONSOR: BRUCE BODGER

TUNGSTEN CARBIDE-COBALT POWDER

Agglomerated and Sintered

1. SCOPE:

1.1 Form:

This specification covers tungsten carbide-cobalt in the form of powder.

1.2 Application:

This powder has been used typically for producing thermal spray coatings to provide wear and fretting resistant surfaces, but usage is not limited to such applications.

2. APPLICABLE DOCUMENTS:

The following publications form a part of this specification to the extent specified herein. The applicable issue of referenced publications shall be the issue in effect on the date of the purchase order.

A. S.A.E. Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AMS xxxx (AMEC 00AB)

2.2 ASTM Publications:

Available from ASTM, 1916 Race Street, Philadelphia, PA 19103-1187.

ASTM B 215 Sampling Finished Lots of Metal Powders

2.3 U.S. Government Publications:

Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

MIL-STD-2073-1 DOD Materiel, Procedures for Development and Application of Packaging Requirements

3. TECHNICAL REQUIREMENTS:

3.1 Composition:

Shall conform to the percentages by weight shown in Table 1, determined by methods acceptable to purchaser.

TABLE 1 – Composition % by Weight

Element	Minimum %	Maximum %
Cobalt	15.0	18.5

Carbon, Total	4.8	5.6
Tungsten	Balance	
Iron	--	1.5
Others (if determined)	--	0.5

3.2 Condition:

As manufactured.

3.3 Properties:

Powder shall conform to the following requirements:

3.3.1 Particle Size Distribution: Shall be as follows: each lot shall show the following cumulative volume percentages when measured by laser light scattering method (Microtrac).

TABLE 2 - Particle Size Distribution % by Volume

Micron Size	Minimum %	Maximum %
+62	--	10
+44	18	35
+22	60	95
+11	92	--

TABLE 3 – Particle Size distribution by Sieve Size

Sieve Size	Minimum %	Maximum %
+270	-	6%
+325	-	25%

3.3.2 Thermal Spraying: Powder shall be capable of producing spray coatings to meet the requirements of AMEC 00AB. Purchaser and vendor shall agree upon standards for acceptance.

3.4 Quality:

Powder, as received by purchaser, shall be thoroughly blended, uniform in color and quality, dry, free flowing and free from foreign materials, clumps and imperfections detrimental to its spraying qualities.

4. QUALITY ASSURANCE PROVISIONS:

4.1 Responsibility for Inspection:

The vendor of powder shall provide all samples for vendor's tests and shall be responsible for performance of all required tests. Purchaser reserves the right to sample and to perform any confirmatory testing deemed necessary to ensure that the powder conforms to the requirements of this specification.

4.2 Classification of Tests:

Tests for all technical requirements are acceptance tests and pre-production tests and shall be performed prior to or on the initial shipment of powder to a purchaser, on each lot, when a change in ingredients and/or processing requires approval by the cognizant engineering organization (see 4.4.2), and when purchaser deems confirmatory testing to be required.

4.2.1 For direct U.S. Military procurement, substantiating test data and, when requested, pre-production material shall be submitted to the cognizant agency as directed by the procuring activity, contracting officer, or request for procurement.

4.3 Sampling and Testing:

Shall be in accordance with ASTM B 215; sufficient powder shall be taken from each lot to perform all required tests. The number of determinations for each requirement shall be as specified in the applicable test procedure or, if not specified therein, not less than three.

4.3.1 When purchaser and vendor have agreed upon a statistical sampling plan, sampling shall be in accordance with such plan in lieu of sampling as in 4.3 and the report of 4.5 shall state such a plan was used.

4.4 Approval:

4.4.1 The process and control procedures, a preproduction sample, or both, whichever is specified, shall be approved by the cognizant engineering organization before production powder is supplied.

4.4.2 The supplier shall make no significant change in ingredients, processes, or controls

from those on which the approval was based, unless the change is approved by the cognizant engineering organization. A significant change is one, which, in the judgment of the cognizant engineering organization, could affect the properties or performance of the powder.

4.5 Reports:

The vendor of a powder shall furnish with each shipment a report showing the results of tests for chemical composition and particle size distribution of each lot and stating the purchase order number, lot number, AMS XXXX, vendor's product designation, and quantity.

4.6 Resampling and Retesting:

If any sample used in the above tests fails to meet the specified requirements, disposition of the powder may be based on the results of testing three additional samples for each original nonconforming sample. Failure of any retest sample to meet the specified requirements shall be cause for rejection of the powder represented. Results of all tests shall be reported.

5. PREPARATION FOR DELIVERY:

5.1 Packaging and Identification:

5.1.1 Powder shall be packaged in sealed containers to protect it from contamination during shipment and under normal dry storage conditions. Seals used on containers shall be so designed that they must be destroyed in order for the container to be opened.

5.1.2 Each individual container shall be legibly identified with not less than the following information, using characters that will not be obliterated by normal handling:

TUNGSTEN CARBIDE-COBALT POWDER

AMS XXXX

MANUFACTURER'S IDENTIFICATION

PURCHASE ORDER NUMBER

QUANTITY

LOT NUMBER

5.1.3 Containers of powder shall be prepared for shipment in accordance with commercial practice and in compliance with applicable rules and regulations pertaining to the handling, packaging, and transportation of the powder to ensure carrier handling and safe delivery.

5.1.4 For direct U.S. Military procurement, packaging shall be in accordance with MIL-STD-2073-1, Commercial Level, unless Level A is specified in the request for procurement.

6. ACKNOWLEDGMENT:

A vendor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders.

7. REJECTIONS:

Powder not conforming to this specification, or to modifications authorized by purchaser, will be subject to rejection.

8. NOTES:

8.1 Revision Indicator:

The (R) symbol is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this specification. If the symbol is next to the specification title, it indicates a complete revision of the specification.

8.2 Definition of terms used in AMS are presented in ARP1917.

8.3 For direct U.S. Military procurement, purchase documents should specify not less than the following:

Title, number, and date of this specification

Quantity of powder desired

Thermal spray acceptance standards and methods for testing (see 3.2)

Level A packaging, if required (see 5.1.4)

8.4 Powder meeting the requirements of this specification has been classified under Federal Standardization Area Symbol "MFFP"

8.5 Key Words:

Thermal spray coatings, wear resistant coatings

8.3. Proposed AMS7882

AMEC 99C

SPONSOR: BRUCE BODGER

TUNGSTEN CARBIDE-COBALT CHROME POWDER

Agglomerated and Sintered

1. SCOPE:

1.1 Form:

This specification covers tungsten carbide-cobalt chrome in the form of powder.

1.2 Application:

This powder has been used typically for producing thermal spray coatings to provide wear and fretting resistant surfaces with a high level of corrosion resistance, but usage is not limited to such applications.

2. APPLICABLE DOCUMENTS:

The following publications form a part of this specification to the extent specified herein. The applicable issue of referenced publications shall be the issue in effect on the date of the purchase order.

S.A.E. Publications:

AMS xxxx (AMEC 00AB)

2.2 ASTM Publications:

Available from ASTM, 1916 Race Street, Philadelphia, PA 19103-1187.

ASTM B 215 Sampling Finished Lots of Metal Powders

2.2 U.S. Government Publications:

Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

MIL-STD-2073-1 DOD Materiel, Procedures for Development and Application of Packaging Requirements

3. TECHNICAL REQUIREMENTS:

3.1 Composition:

Shall conform to the percentages by weight shown in Table 1, determined by methods acceptable to purchaser.

TABLE 1 – Composition % by Weight

Element	Minimum %	Maximum %
Cobalt	8.5	11.5
Chromium	3.0	5.0
Tungsten	Balance	
Carbon, Total	3.2	5.5
Iron	--	1.0
Others (if determined)	--	2.5

3.2 Condition:

As manufactured.

3.3 Properties:

Powder shall conform to the following requirements:

3.3.1 Particle Size Distribution: Shall be as follows: each lot shall show the cumulative volume percentages when measured by laser light scattering method (Microtrac).

TABLE 2 - Particle Size Distribution % by Volume

Micron Size	Minimum %	Maximum %
+62	--	10
+44	18	35
+22	60	95
+11	92	--

TABLE 3 – Particle Size distribution by Sieve Size

Sieve Size	Minimum %	Maximum %
+270	-	5%
+325	-	25%

3.3.2 Thermal Spraying: Powder shall be capable of producing spray coatings to meet the

requirements of AMEC 00AB. Purchaser and vendor shall agree upon standards for acceptance.

3.4 Quality:

Powder, as received by purchaser, shall be thoroughly blended, uniform in color and quality, dry, free flowing and free from foreign materials, clumps and imperfections detrimental to its spraying qualities.

4. QUALITY ASSURANCE PROVISIONS:

4.1 Responsibility for Inspection:

The vendor of powder shall provide all samples for vendor's tests and shall be responsible for performance of all required tests. Purchaser reserves the right to sample and to perform any confirmatory testing deemed necessary to ensure that the powder conforms to the requirements of this specification.

4.2 Classification of Tests:

Tests for all technical requirements are acceptance tests and pre-production tests and shall be performed prior to or on the initial shipment of powder to a purchaser, on each lot, when a change in ingredients and/or processing requires approval by the cognizant engineering organization (see 4.4.2), and when purchaser deems confirmatory testing to be required.

4.2.1 For direct U.S. Military procurement, substantiating test data and, when requested, pre-production material shall be submitted to the cognizant agency as directed by the procuring activity, contracting officer, or request for procurement.

4.3 Sampling and Testing:

Shall be in accordance with ASTM B 215; sufficient powder shall be taken from each lot to perform all required tests. The number of determinations for each requirement shall be as specified in the applicable test procedure or, if not specified therein, not less than three.

4.3.1 When purchaser and vendor have agreed upon a statistical sampling plan, sampling shall be in accordance with such plan in lieu of sampling as in 4.3 and the report of 4.5 shall state such a plan was used.

4.4 Approval:

4.4.1 The process and control procedures, a preproduction sample, or both, whichever is specified, shall be approved by the cognizant engineering organization before production powder is supplied.

4.4.2 The supplier shall make no significant change in ingredients, processes, or controls from those on which the approval was based, unless the change is approved by the cognizant engineering organization. A significant change is one, which, in the judgment of the cognizant engineering organization, could affect the properties or performance of the powder.

4.5 Reports:

The vendor of a powder shall furnish with each shipment a report showing the results of tests for chemical composition and particle size distribution of each lot and stating the purchase order number, lot number, AMS XXXX, vendor's product designation, and quantity.

4.6 Resampling and Retesting:

If any sample used in the above tests fails to meet the specified requirements, disposition of the powder may be based on the results of testing three additional samples for each original nonconforming sample. Failure of any retest sample to meet the specified requirements shall be cause for rejection of the powder represented. Results of all tests shall be reported.

5. PREPARATION FOR DELIVERY:

5.1 Packaging and Identification:

5.1.1 Powder shall be packaged in sealed containers to protect it from contamination during shipment and under normal dry storage conditions. Seals used on containers shall be so designed that they must be destroyed in order for the container to be opened.

5.1.2 Each individual container shall be legibly identified with not less than the following information, using characters that will not be obliterated by normal handling:

TUNGSTEN CARBIDE-COBALT CHROME POWDER

AMS XXXX

MANUFACTURER'S IDENTIFICATION

____

PURCHASE ORDER NUMBER

____

QUANTITY

____

LOT NUMBER

____

5.1.3 Containers of powder shall be prepared for shipment in accordance with commercial practice and in compliance with applicable rules and regulations pertaining to the handling, packaging, and transportation of the powder to ensure carrier handling and safe delivery.

5.1.4 For direct U.S. Military procurement, packaging shall be in accordance with MIL-STD-2073-1, Commercial Level, unless Level A is specified in the request for procurement.

6. ACKNOWLEDGMENT:

A vendor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders.

7. REJECTIONS:

Powder not conforming to this specification, or to modifications authorized by purchaser, will be subject to rejection.

8. NOTES:

8.1 Revision Indicator:

The (R) symbol is for the convenience of the user in locating areas where technical

revisions, not editorial changes, have been made to the previous issue of this specification. If the symbol is next to the specification title, it indicates a complete revision of the specification.

8.2 Definition of terms used in AMS are presented in ARP1917.

8.3 For direct U.S. Military procurement, purchase documents should specify not less than the following:

Title, number, and date of this specification

Quantity of powder desired

Thermal spray acceptance standards and methods for testing (see 3.2)

Level A packaging, if required (see 5.1.4)

8.4 Powder meeting the requirements of this specification has been classified under

Federal Standardization Area Symbol "MFFP"

8.5 Key Words:

Thermal spray coatings, wear resistant coatings

8.4. Proposed HVOF grinding specification

Proposed

GRINDING OF HVOF SPRAYED TUNGSTEN CARBIDE COATINGS APPLIED TO HIGH STRENGTH STEELS

DRAFT

Jon L. Devereaux, Sponsor

1.0 SCOPE

1.1 Purpose

This specification covers engineering requirements for the grinding of tungsten carbide High Velocity Oxygen/Fuel (HVOF) thermal spray coatings applied to high strength steels (220 ksi and above).

1.2 Application

This process has been used typically to grind tungsten carbide HVOF coatings applied in accordance with AMS 2447 to high strength steels for applications requiring wear, heat, and corrosion resistance or dimensional restoration, such as aircraft landing gear components. However, usage is not limited to such applications. This process specification does not cover superfinishing of HVOF applied coatings.

1.3 Safety - Hazardous Materials

While the materials, methods, applications, and processes described or referenced in this specification may involve the use of hazardous materials, this specification does not address the hazards which may be involved in such use. It is the sole responsibility of the user to ensure familiarity with the safe and proper use of any hazardous materials and to take necessary precautionary measures to ensure the health and safety of all personnel involved.

2.0 APPLICABLE DOCUMENTS

2.1 The following publications form a part of this specification to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order.

2.2 S.A.E. Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AMS 2447 Coating, Thermal Spray High Velocity Oxygen/Fuel Process

AMEC 99B Tungsten Carbide-Cobalt Powder

AMEC 99C Tungsten Carbide-Cobalt Chrome Powder

2.3 ASTM Publications: Available from ASTM, 100 Barr Harbor Drive, West Conshocken, PA 19428-2959

3.0 TECHNICAL REQUIREMENTS

3.1 Equipment

3.1.1 Grinding equipment: Grinding equipment shall be capable of maintaining grinding wheel speed, workpiece speed, traverse or cross feed speed, and down feed (infeed) in increments necessary to avoid surface degradation of the part. Provisions shall be made to supply a constant application of cutting fluid (coolant) to the working surface of the wheel at the grinding zone interface.

3.2 Materials

3.2.1 Grinding wheels: Grinding wheels shall be labeled with the complete grinding wheel specification including abrasive type, grit size, grade, structure, bond type and maximum operating speed. Unless otherwise specified, diamond abrasive resin bonded grinding wheels shall be used.

3.2.2 Cutting Fluids (Coolants): A suitable cutting fluid shall be used which does not have an adverse effect on the part being ground. Recirculating cutting fluids shall be continuously filtered to minimize recycling grinding residue and swarf. A coolant nozzle sufficiently wide to flood the entire width of the grinding wheel shall be used. For proper application of the cutting fluid, the cutting fluid nozzle should be designed to deliver cutting fluid at a speed equal to or slightly faster than the peripheral grinding wheel speed. (See Section 8.4.2).

3.3 Preparation

3.3.1 Cleaning: Protective coatings and other foreign materials shall be removed from parts prior to grinding to preclude contamination of coolant and wheels. Coolants and grinding residuals that have a deleterious effect on the part shall be removed after grinding. Cleaning materials shall not corrode or otherwise degrade the surfaces of the part. Where process delay time is such that corrosion might occur, parts shall be adequately protected after cleaning.

3.4.1 Grinding Process Control: The grinding process shall be performed in accordance with *Paragraph 3.5* to result in metallurgically sound parts. All speeds, feeds, and stock removal parameters are actual and not necessarily machine or indicator readings. Prior to grinding, clean all surfaces to be ground as stated in Paragraph 3.3.1.

3.4.2 Balance the grinding wheel assembly at the time the wheel is mounted. If the grinding wheel remains on the machine arbor it will not need to be balanced again. If the grinding wheel is removed from the machine/arbor it should be re-balanced at the next mounting. True the wheel face so that it is geometrically correct for the application and runs concentric with the centerline of the arbor assembly (see Section 8.4.1). Dress the grinding wheel frequently during use to keep the wheel open with sharp grit exposed to freely cut the work material.

3.4.3 Flood the entire width of the grinding wheel at the wheel-work interface with a filtered continuous flow of approved cutting fluid.

3.5 Grinding Parameters.

3.5.1 Use a peripheral grinding wheel speed of 5200 to 6500 surface feet per minute (SFPM).

3.5.2 Use cross feeds/traverse rate and infeeds as follows:

3.5.2.1 For cylindrical and internal grinding, the roughing infeed (on the diameter) shall not exceed a maximum of 0.002 inch for 100 or 120 grit, 0.0015 inch for 150 grit, 0.001 inch for 180 grit, 0.0008 inch for 220 grit, 0.0006 inch for 320 grit, or 0.0004 inch for 400 grit for each pass. Incremental infeed shall be done at each end of the traverse or crossfeed to maintain wheel face flatness.

3.5.2.2 For cylindrical and internal grinding, a minimum of 0.002 inch stock removal per side (0.004 inch on diameter) is required for finish grinding. The finishing infeeds (on the diameter) shall not exceed a maximum of 0.0005 inch for 100 or 120 grit, 0.0004 inch for 150 grit, 0.0003 inch for 180 grit, 0.0002 inch for 220 grit, or 0.0001 inch for 320 or 400 grit for each pass. Incremental infeed shall be done at each end of the traverse or crossfeed to maintain wheel face flatness.

3.5.2.3 For cylindrical and internal grinding, use a roughing cross feed or traverse rate of 1/6 to 1/8 wheel width per workpiece revolution. Use a finishing cross feed or traverse rate of 1/8 to 1/12 wheel width per workpiece revolution.

3.5.2.4 For surface grinding, the cross feeds shall not exceed 0.080 inch per pass.

3.5.2.5 For surface grinding, the roughing infeed (depth of cut) shall not exceed a maximum of 0.001 inch for 100 or 120 grit, 0.0008 inch for 150 grit, 0.0005 inch for 180 grit, 0.0004 inch for 220 grit, 0.0003 inch for 320 grit, or 0.0002 inch for 400 grit for each pass.

3.5.2.6 For surface grinding, a minimum of 0.002 inch stock removal is required for finish grinding. The finishing infeeds (depth of cut) shall not exceed a maximum of 0.0005 inch for 100 or 120 grit, 0.0004 inch for 150 grit, 0.0003 inch for 180 grit, 0.0002 inch for 220 grit, or 0.0001 inch for 320 or 400 grit.

3.5.2.7 When grinding ID or OD surfaces, the work should have a speed of 60 to 100 surface feet per minute.

3.5.2.8 The following chart contains general guide lines for surface finish generation for the grit sizes indicated above. Traverse grinding with spark-out passes may produce finer finishes than shown here.

Grit Size	Roughing Mode	Finishing Mode
100-120	32–36 AA	20-32 AA
150	22-26 AA	14-20 AA
180	18-22 AA	12-14 AA
220	12-16 AA	10-12 AA
320-400	8-11 AA	6-10 AA

a. Note: Superfinishing of surfaces is generally indicated by measured surface finishes less than 5 AA. Grit sizes used in the ranges above are not capable of producing super finished surfaces.

b. AA = Arithmetic Average (Micro-inch) surface finish.

3.6 Each of the following parameters shall be met when selecting a grinding wheel.

3.6.1 Abrasive – Diamond.

3.6.2 Bond – Resin

3.6.3 Grit or Grain Size – 100 to 400 grit

3.6.4 Hardness or Grade – H, L, M, N, P, or R

3.6.5 Concentration – 75 to 125

3.7 Inspection requirements: All ground surfaces shall be visually inspected without magnification for evidence of overheating (discoloration), cracks, flaking or peeling.
Ground surfaces shall be checked for surface finish.

3.8 Fluorescent Penetrant Inspection: All ground surfaces shall be inspected by fluorescent penetrant inspection in accordance with ASTM E 1417 or approved alternate procedure.

4.0 QUALITY ASSURANCE

4.1 Monitoring of the process and examination of the finished items shall be in compliance with local quality assurance provisions which ensure that the requirements of this specification are met.

4.2 The coated surface shall be free from heat checks, pull-outs, cracks, and separation from the base metal. Examine for heat checks and pull-outs visually using up to 40X magnification. Penetrant inspection, in accordance with ASTM E 1417, shall be used to check for cracking caused by, or revealed by, grinding; and separation of the thermal spray coating from the base metal along the periphery of the coating. Etching prior to penetrant inspection is not required.

4.3 The finished surface shall meet the machine finish required by the drawing. Unless otherwise specified, finishes which are finer than the drawing callout shall not be cause for rejection.

4.4 The process description and control factors, a ground part, or both, whichever is specified, shall be approved by the cognizant engineering organization before production finish ground parts are supplied.

4.5 The processor of parts ground in accordance with this specification shall make no significant change to the process description, or to the materials, processes, or controls referenced in the process description (see Figure 1) unless the change is approved by the

cognizant engineering organization. A significant change is one which deviates more than plus or minus ten percent of the approved baseline.

4.6 If the results of any inspection fail to meet the specified requirements, the process is nonconforming. No additional parts shall be processed until the process is corrected and new specimens are coated and ground. Results of all tests shall be recorded and when requested, reported. Purchaser shall be notified of all parts ground since the last successful inspection.

5.0 PREPARATION FOR DELIVERY

5.1 Finish ground parts shall be handled and preserved and packaged to ensure that the required physical characteristics and properties of the ground coating are preserved.

5.2 Packages of parts shall be prepared for shipment in accordance with commercial practice and in compliance with applicable rules and regulations pertaining to the handling, packaging, and transportation of the parts to ensure carrier acceptance and safe delivery.

6.0 ACKNOWLEDGMENT

6.1 Processor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders.

7.0 REJECTIONS

7.1 Parts, which have non-compliant coating that does not conform to this specification, or to modifications authorized by purchaser, will be subject to rejection.

8.0 NOTES

8.1 Dimensions are in inches.

8.2 Procurement documents should specify not less than the following:

AMS xxxx

Type of coating to be ground

Coating thickness required

Coating acceptance criteria if not specified herein

Quantity of parts to be ground

8.3 Definitions

8.3.1 <u>Balance (Dynamic):</u> Dynamic balance is the balancing of the complete rotating

assembly; grinding wheel, mounting arbor, and the machine spindle. Depending on the balancing machine, the balance condition is measured and corrected at wheel speed.

8.3.2 Balance (Static): Static balance is the balance of the grinding wheel mounted on an arbor, typically balanced on a pair of knife-edges.

8.3.3 Concentration: The amount of superabrasive material contained in a unit volume of the grinding wheel. The measurement is based on the number of carats of superabrasive material per unit volume. Typical concentration numbers are in the range of 30 to 175. A concentration of 100 does not mean 100 percent and therefore is not the maximum concentration. A concentration of 100 means that there are 4.4 carats of abrasive per cm^3 (or 72 carats/cu. in. or 25 volume percent). The abrasive concentration of the selected grinding wheel, for grinding HVOF applied tungsten carbide coatings, is based upon the area of contact between the wheel and workpiece. A large contact area dictates a low concentration and a small area of contact a higher concentration so the wheel can hold form and resist premature wear. Since OD grinding generally has smaller contact areas than ID grinding, the concentration of the abrasive in the grinding wheel should generally be higher for OD grinding and lower for most ID applications.

8.3.4 Coolant: Coolant is the misnomer for cutting fluid. The cutting fluid not only cools; it also lubricates and washes away chips and debris. The better term is cutting fluid.

8.3.5 Cutting Fluid: Cutting fluid is the fluid used to cool, lubricate, and wash clean a machining process. Cutting fluids may be oils, water-based synthetic, or soluble oils and gases.

8.3.6 Dressing: Dressing/sharpening is the process of conditioning the wheel surface so as to achieve a certain grinding behavior. Dressing a resin-bonded grinding wheel entails removing some of the bond to expose the grain. This is accomplished by using an aluminum oxide or silicone carbide stick to "stick" the wheel. "Sticking" is best performed wet.

8.3.7 Grade: The grade of a grinding wheel usually refers to the hardness of the bond system. This is determined by the size, type, and amount of filler materials incorporated in the plastic binder material. There is a standard code for grinding wheel grades.

8.3.8 Grain Size: The grain size refers to a number which corresponds to the U.S. Standard wire mesh size screen used for sizing the abrasive grain. This size is also defined by average particle diameter.

8.3.9 Grit Size: Another term for abrasive grain size.

8.3.10 Infeed: The infeed or down-feed is the feed motion of the grinding wheel into the workpiece.

8.3.11 Spark-out: This is the grinding of a workpiece at the end of the stock removal cycle without engaging any further downfeed (infeed). The grinding forces are allowed to subside with time, ensuring a precision surface.

8.3.12 Superabrasive: Diamond or Cubic Boron Nitride (CBN) abrasives.

8.3.13 Superfinishing: A process used to produce high surface finishes with an average surface roughness of 8 µinches Ra, or better, and a higher bearing area ratio, Tp, than ground surfaces.

8.3.14 Surface Finish: Surface finish is the smoothness of the machining marks on the surface of a workpiece. Surface finish is measured by moving a precision stylus across the surface and measuring the amplitude of the fluctuations of the stylus.

8.3.15 Swarf: Swarf is the mass of chips and debris remaining after a grinding process.

8.3.16 Thermal Damage: Thermal damage is metallurgical damage which occurs to a material when it is subjected to temperatures which will affect its metallurgical structure.

8.3.17 Truing: Truing a grinding wheel is the procedure of making the grinding wheel geometrically correct for the application and to ensure it is rotating concentric to the center line of the spindle.

8.3.18 Brake Truing Device: A brake controlled truing device is a grinding wheel mounted on an arbor and bearing housing, which has a friction brake to limit its speed. Such a brake-controlled truing device can be used to true resin-bonded superabrasive grinding wheels. Note: Brake controlled truing devices are useful for truing grinding wheels up to 12 inch diameter.

8.3.19 Wheel Speed: Wheel speed is the peripheral speed of the grinding wheel. It is calculated by the following formula: Wheel Speed (Surface Feet per Minute) = Wheel Diameter (in inches) x RPM x .262. For metric equivalent, Meters per Second (m/sec. x 196.85 = SFPM

8.4 Key Words: HVOF, Wear Resistant, Corrosion Resistance, Dimensional Restoration, Superabrasive, Concentration, Cutting Fluid, Dress, True

Figure 1

Grinding Process Control Sheet

APPLICATION:

PART NAME:____________________ MACHINE NAME:______________

PART NUMBER (VENDOR CODE):____________________(________)__

WHEEL CLASSIFICATION:______________________________

WHEEL MANUFACTURER:______________________________

WHEEL: DIA________ RPM________ SFPM________ WIDTH________

WORK PIECE DATA:

DIAMETER__________ RPM__________ SFPM__________ LENGTH OF TRAVERSE_____

AMOUNT OF MATERIAL TO BE REMOVED BY GRINDING______________________________

BASE MATERIAL______________________ UTS OR HARDNESS______________________

CUTTING FLUID__________________________________ CONCENTRATION____________

GRINDING PARAMETERS

TRAVERSE GRIND: ROUGHING	TRAVERSE GRIND: FINISHING
_________ Workpiece RPM	_________ Workpiece RPM
_________ Roughing Traverse Rate	_________ Finishing Traverse Rate
_________ Traverse Rate (Inches/Minute)	_________ Traverse Rate (Inches/Minute)
_____ Sec. Traverse Time for Length of Traverse	_____ Sec. Traverse Time per Length of Traverse
_________ Rough Infeed per End	_________ Finish Infeed per End
Rough Until _________ From Finish Size	
_________ Finish Infeed per End	
_____ Sec. Dwell Time Left	_________ Dwell Time Left
_____ Sec. Dwell Time Right	_________ Dwell Time Right
_________ No. of Spark-out Passes	_________ No. of Spark-out Passes
_________ Total Cycle Time	_________ Total Cycle Time

TOTAL DIMENSIONAL TOLERANCE________________ SURFACE FINISH REQUIRED__________ µin R_a

SPECIAL MACHINING INSTRUCTIONS: Check wheel speed before starting.

Verify roughing traverse rate (xxx Seconds/xxx inches length of roughing traverse) prior to grinding.

Verify finishing traverse rate (xxx Seconds/xxx inches length of finishing traverse) prior to grinding.

OPERATOR: ________________________________ CERTIFICATION NO: __________________

APPROVAL: ____ DATE: __________________

PREPARED UNDER THE JURISDICTION OF AMS COMMITTEE "B"

8.4.1. Truing & Dressing of Large Diameter Diamond Grinding Wheels

Small brake controlled truing devices, which typically have a 3" diameter truing wheel, are designed for use on grinding wheels up to 12" diameter. The use of small brake controlled truing devices on large diameter grinding wheels (14" to 36") results in excessive time required to true a wheel with a number of truing wheels being consumed in the process.

There are two options available; one is to send the wheel back to the grinding wheel manufacturer for re-truing. The second option is to re-true the wheel locally. This can be accomplished on the machine; it does however require the manufacture of tooling to accept a conventional grinding wheel for the machine.

Procedure for truing large diameter diamond grinding wheels (14" to 36"):

1. Manufacture an arbor and flange assembly to mount a 10" x 1" or 2" wide x hole size conventional grinding wheel with provisions for a dog to turn the assembly. Wheel diameter can be larger or smaller depending on the size of the O.D. grinding machine. The conventional abrasive wheel mounted on this arbor/flange fixture is mounted in the work position on the O.D. machine.

2. The recommended conventional abrasive truing wheel would be 39C60I8VK or equivalent. As a general guideline, the truing wheel should be 60 to 100 grit.

3. At the point of contact of the two wheels, the diamond wheel that needs truing and the conventional abrasive truing wheel, the preferred method is for both wheels to be running in the same direction. Some machines do not allow for this set-up (i.e. some machines do not have capability to reverse the direction of rotation of the workpiece).

4. The diamond wheel should be running at spindle speed. Usually on O.D. grinders this is about 5600 SFPM (28 m/s).

5. Adjust the conventional abrasive wheels mounted in the work position to 1500 SFPM (7 m/s) or about 1/3 the surface footage of the diamond wheel.

6. Traverse the diamond wheel across the conventional abrasive wheels face at 30 to 60 inches per minute. Traverse the entire width to ensure that a radius is not formed into the wheel face.

7. Infeed the diamond wheel into the truing wheel 0.0005" to 0.001" per traverse until the wheel face is trued. Color the wheel face using a wax china marker, this will aid in visually being able to see when truing is complete. **DO NOT** use liquid ink or Dykum, these liquids leach into the diamond wheels pores and will result in truing off more usable diamond depth than is necessary.

8. After truing, stick dress the diamond wheels face to sharpen the wheel for grinding. The recommended dressing stick specification is 38A (one or two grit sizes finer than the

diamond in the wheel) HVBE.

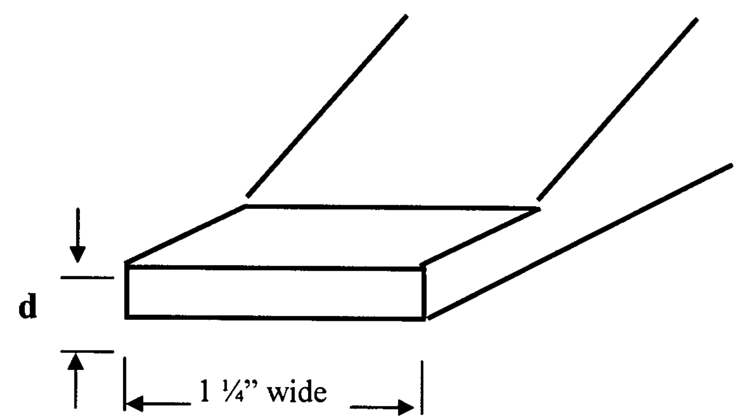
9. Dial indicate the wheel to ensure wheel is round and face is flat.

This results in a very large brake controlled truing device, significantly more efficient and capable of truing large diameter wheels than the small brake controlled truing devices designed and intended for use on wheels 12” and less in diameter.

8.4.2. Calculation of nozzle opening for proper cutting fluid application

The velocity of the cutting fluid should be equal to or slightly greater than peripheral velocity of the grinding wheel. An example of how to size the cutting fluid nozzle opening is provided here. For this example, assume the cutting fluid delivery pump is rated at 50 U.S. gallons per minute (gpm). Also, for this example assume a peripheral grinding wheel speed of 6,000 surface feet per minute (SFPM).

For a one inch wide grinding wheel, make the nozzle slightly wider than the wheel width or about plus 1/8" on each side. Therefore, for a one inch wide wheel, select nozzle width of 1.25".



Area (of nozzle opening) = 1.25 x d in^2

Grinding wheel speed 6,000 SFPM x 12 in/ft = 72,000 IPM

Volume flow = Nozzle area x wheel speed

50 U.S. gal/min x 231 in^3/U.S. gallon = (1.25 x d in^2) (72,000 in/min)

$$11{,}550 \ \text{in}^3/\text{min} \quad = \quad 90{,}000 \times d \ \ \text{in}^3/\text{min}$$

$$d = 0.128''$$

To get fluid exit velocity slightly higher than grinding wheel speed, select a nozzle opening, d, of 0.125".

9. Implementation

9.1. General implementation issues

Implementing HVOF in place of EHC on landing gear has proved to be an important learning experience in material and process substitution. The major issues are summarized here and some items are discussed in more detail below:

- **Teaming** – In attempting to qualify and implement a new technology on flight-critical components, it is essential to involve the entire stakeholder community from the outset and identify important areas of concern. Contributions from program offices, system support offices, depot engineers, and OEMs were made toward development of the JTP and all results, positive and negative, were presented to them for evaluation and consideration. To make the program manageable, *ad hoc* subteams were put together to resolve specific issues, such as fatigue testing and coating integrity. Various team members and organizations volunteered their services and test facilities to acquire data, develop specifications, and carry out other tasks critical to the success of the overall project. Although commercial competitors were involved in the team, they exhibited a remarkable degree of cooperation in developing a common technology base.
- **Data acquisition** – The whole team has been kept aware of all significant data through biannual program review meetings and a team web site where all data is posted. When an unexpected issue arose, such as the delamination of the HVOF coatings at high stress, it was again important to involve the stakeholder community and obtain their criteria for acceptable performance. Team member orgainizations contributed their own data to the effort whenever items of particular concern or interest arose. There must be flexibility (both programmatic and financial) built into any project of this type so that unplanned testing can be conducted to address unforeseen issues.
- **Implementation** – From the outset the project was designed to implement directly in the depots and vendors. Equipment was installed by the program in several depots and team experts from industry trained depot personnel and helped the depots to develop process specifications. While the original expectation was that all depositions on test items would be done in the depots, this was found to be impractical in some cases because of the production demands of the depots. Therefore in most cases materials analyis specimens were coated at commercial vendors.
- **Specifications and standards** – It was made clear early in the program that implementation would require the existence of standards and specifications to which engineers could refer. For this reason the team assigned specific members to develop specifications and shepherd them through the relevant AMEC committees.

9.2. Performance observations – differences between HVOF and EHC

Based on all of the materials testing, it was concluded that on high-strength steels that are used to fabricate landing gear components, the fatigue, wear and impact-resistant properties of the HVOF WC/17Co and WC/10Co4Cr coatings are superior to those of EHC coatings. Inconsistent results were obtained for corrosion testing of both the HVOF and EHC coatings, but examination of all of the B117 salt fog and atmospheric corrosion test results, together with the favorable performance of WC/17Co coatings in service on the P3 aircraft, lead to the conclusion that the HVOF coatings should perform at least as well as EHC coatings. There are no hydrogen embrittlement issues associated with HVOF coatings and the testing indicated that re-embrittlement is less of an issue with HVOF coatings than with EHC. All of the rig and flight testing performed to date has indicated excellent performance of the WC/17Co and WC/10Co4Cr coatings. This is true even of components in situations where materials testing had raised coating integrity and delamination concerns.

The one issue that still can impact implementation of the HVOF coatings on landing gear components is delamination at high stresses and strains. It has been shown that the delamination is dependent on the thickness of the coating and on how the stresses are applied. Thus, for example, OO-ALC has shown that on a hollow cylinder representative of a landing gear piston, a WC/17Co coating will remain intact in tension/compression bending ($R = -0.33$) to beyond the yield stress of the base material, whereas it will delaminate at about 80% of the yield stress (for a 0.010"-thick coating) for fully-reversed tension/compression stresses applied axially. The Air Force believes that the bending test is more representative of real-life stresses applied to landing gear and thus they are continuing to implement HVOF coatings on their landing gear components. On the other hand, Navy structural engineers believe that the HVOF coatings should be able to remain intact up to the yield stress for fully-reversed axially applied stress and therefore are reluctant to approve the coatings on carrier-based aircraft that are subjected to high stress. But this concern should not prevent implementation of the HVOF coatings on land-based aircraft and helicopters.

The original specifications for surface finishes and seals that have been developed over the years for EHC plating cannot be used for HVOF coatings. If a surface finish of 16μ" Ra, typical for EHC, is used on an HVOF-coated landing gear inner cylinder it will rapidly degrade the seal and cause excessive leakage. On the other hand, a superfinished HVOF surface with <4μ" Ra gives much longer seal life than is obtained with EHC, and shows little or no degradation of the coated surface over time. It has been found that it is no longer sufficient simply to specify an average roughness (Ra), or a root mean square roughness (RMS), surface finish, as is traditionally done with EHC. For many applications users are specifying more detailed surface parameters that can be achieved with superfinishing equipment, such as bearing area ratio (Tp), peak-to-valley height (Rt), peak height (Rp), and valley depth (Rv).

For applications such as landing gear it is possible that HVOF WC/Co or wC/CoCr will approach the ideal of a "lifetime coating" that will not need to be reworked for the life of the component (or at least for many maintenance cycles). However, this requires a

recognition that the maintenance methods commonly used for chrome plated parts can no longer apply. For example, many plated parts are assumed always to deteriorate in service and are therefore always stripped and the substrate examined by NDI (magnetic particle, MPI, or fluorescent penetrant inspection, FPI) for damage or cracks. If the cost savings associated with the extended life of HVOF coatings are to be realized maintenance cannot be done in this way since it will result in unnecessary stripping and recoating. Some users are adopting the approach that FPI of the coated part is sufficient, while other users are endeavoring to develop better through-coating inspection procedures.

The corrosion data is another area in which HVOF coatings perform in a different way from EHC coatings. EHC-plated parts tend to corrode by liquid penetration followed by substrate corrosion and undercutting of the coating. The chrome plate itself does not corrode, but it tends to remain in place until it loses its support and flakes off. HVOF coatings, on the other hand, experience corrosion of the matrix alloy. This could lead to gradual dissolution and roughening of the surface, leading to seal damage and a gradual increase of seal leakage. Neither of these failure mechanisms is necessarily always "better" than the other, but the difference needs to be recognized in planning implementation and maintenance.

9.3. Implementation

The Air Force is proceeding with implementation of HVOF coatings on landing gear components at Ogden ALC, the primary overhaul location for landing gear. As of March 2003, a project implementation team had been established at OO-ALC and they expect a phased transition based on capacity. They have approved the application of WC/17Co and WC/10Co4Cr coatings up to 0.010" thickness on the components summarized in Table 9-1.

Table 9-1. Components Approved for HVOF at OO-ALC

C-5 MLG outer pitch actuator	C-5 gudgeon pin
C-5 MLG ball screw	F-16 MGL tension strut
F-16 MLG axle	A-10 NLG charging pin
A-10 NLG inner piston	KC-135 MLG aft axle
KC-135 MLG forward axle	KC-135 NLG piston
F-15 brake drive keys	B-2 rub strips

Fixturing is being developed for spraying these parts and the coatings will be applied under local engineering authority.

The Air Force has agreed to invest $3.5 million of non-environmental funds to expand Ogden's HVOF spraying capabilities to meet their workload. OO-ALC is projecting a total of 10 spray booths, four considered small, four medium, and two large for processing different size components. These spray booths would be used for processing more than just landing gear components as most of the actuators on Air Force aircraft are also processed at Ogden.

The HVOF systems currently in operation at OO-ALC and NADEP-JAX are full-production systems with fixturing for manipulation of various types of components and

robots on which the HVOF spray guns are mounted. NADEP-JAX has not projected the total number of spray booths required, but does plan on acquiring more as the number of components approved for HVOF processing increases.

As a result of the HCAT program on landing gear Goodrich has specified HVOF WC/CoCr as the baseline coating in place of hard chrome plate on the landing gear for the Joint Strike Fighter (JSF). HVOF will therefore be used for seal surfaces and axle bearings, lugs, pins, and landing gear hydraulic actuators.

As a result of the program Messier-Dowty has installed HVOF coating equipment at their Ajax, Ontario plant, which manufactures F-18 landing gear, among others. At this point, the technology has not been approved for carrier-based F-18 use because of the coating integrity issues outlined in Section 9.2.

Early in 2003 Ogden ALC demonstrated their first "green landing gear" overhaul, using HVOF for all wear surfaces (previously chrome), IVD aluminum for external surfaces and sputtered aluminum for internal surfaces subject to corrosion (previously cadmium plated).

9.4. Specifications and standards

One of the key end user/OEM issues is the availability of standards and specifications related to the powder used for HVOF coatings, application procedures for the coatings, and grinding procedures for the coatings. The HCAT has worked with the SAE Aerospace Metals Engineering Committee to develop four separate specifications in these areas (see Section 8). Those related to powder and coating deposition were completed and forwarded to SAE Aerospace Materials Committee B, who approved them in February 2003. The following are the designations:

- AMS 2448 – "Application of Tungsten Carbide Coatings on Ultra-High-Strength Steels, High-Velocity Oxygen/Fuel Process"
- AMS 7881 – "Tungsten Carbide-Cobalt Powder, Agglomerated and Sintered"
- AMS 7882 – "Tungsten Carbide-Cobalt Chromium Powder, Agglomerated and Sintered"

A specification for grinding and superfinishing of the coatings has been drafted and is in the approval process. All of these specifications can now be utilized by any manufacturing or overhaul depot and their use will result in consistency between facilities with respect to coating properties.

In addition, aerospace companies have developed their own specifications:

- Boeing has updated BAC 5851, the company's specification for thermal spray.
- United Technologies Hamilton Sundstrand has developed HS 4412 for HVOF in place of EHC.
- Delta Airlines is now qualified for applying HVOF in place of EHC in landing gear repair, and has been particularly forward in developing surface finish specifications.

- Messier Dowty uses AMS 2447, and will doubtless specify AMS 2448 where appropriate.

9.5. Cost observations

As with all material and process replacements the life cyle costs vary from one location to another.

As indicated in Section 7, the annual operating cost savings at a major commercial landing gear overhaul facility for replacing 88% of their chrome plating operations with HVOF thermal spraying range from $195,600 to $210,700. Payback on the capital investment of installing HVOF systems would be realized within about 3½ years. Although the annual operating costs for both EHC and HVOF would be different at other facilities based on labor rates, types of equipment used and other factors, it is still anticipated that there would be substantial savings by replacing as much of their chrome plating operations as possible with HVOF. Additional cost savings that would be realized are associated with the estimated 50-100% extension of service life for the WC/Co or WC/CoCr coatings over EHC coatings. In the future, as HVOF-coated landing gear components come into the facility for inspection, fewer will require overhaul compared to what would have been expected with EHC coatings and thus there will be a reduction in labor and material costs associated with overhaul operations since the components could be returned to service. In addition, the elimination of process hydrogen embrittlement and the reduction of environmental embrittlement will reduce the risk (and therefore the annual cost) of landing gear service failures.

It should also be mentioned that the CBA described in Section 7 did not take into account any increases in costs associated with EHC resulting from more stringent environmental or worker safety regulations. If, for example, the PEL for hexavalent chromium is reduced as is expected, then the cost for chrome plating will increase, thereby making the operating cost savings even greater for HVOF.

Although not discussed in Section 1, a cost analysis was performed to determine if it would be more cost-effective to outsource the HVOF coating operations to a job shop. The results showed that it would be less costly to establish an in-house HVOF coating capability. Therefore, the facility for which the CBA was performed has decided to acquire and install HVOF systems in its repair shop to process landing gear components.

9.6. Regulatory Compliance and Acceptance

The principal environmental and worker safety issues associated with HVOF thermal spraying are air emissions containing overspray particles and the noise of the gun itself. At this point there are no serious regulatory issues associated with HVOF deposition of WC/Co or WC/CoCr at any of the depots. In each of the depots that have adopted the technology, the equipment is properly installed in soundproof booths and excess (overspray) powder is trapped in a bag-house filter system. The deposition is carried out in a well-controlled manner using robotic systems to prevent any operator exposure to noise or dust during the deposition process.

All of the depots involved in the HCAT project already had other types of thermal spray

equipment in operation, such as flame or plasma spray, and therefore they had the appropriate air handling equipment (e.g., exhaust hoods, bag houses) available and also had the appropriate air permits to cover operation of the HVOF systems.